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RTO-EN-9

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO EDUCATIONAL NOTES 9

Development and Operation of UAVs for Military and Civil Applications

(Développement et utilisation des avions sans pilote (UAV) pour des applications civiles et militaires)

This report is a compilation of the edited proceedings of the "Development and Operation of UAVs for Military and Civil Applications" course held at the von Kármán Institute for Fluid Dynamics (VKI) in Rhode-Saint-Genèse, Belgium, 13-17 September 1999.

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The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by 7 Panels, dealing with:

- SAS Studies, Analysis and Simulation
- SCI Systems Concepts and Integration
- SET Sensors and Electronics Technology
- IST Information Systems Technology
- AVT Applied Vehicle Technology
- HFM Human Factors and Medicine
- MSG Modelling and Simulation

These Panels are made up of national representatives as well as generally recognised 'world class' scientists. The Panels also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Development and Operation of UAVs for Military and Civil Applications

(RTO EN-9)

Executive Summary

This international Special Course brought together 60 engineers and scientists (47 observers and 13 lecturers) from 14 different countries. It was a full five-day course organized from 13th to 17th September 1999.

The first lecture, "UAVs: Overview of the Current Situation and Potential for the Future", emphasized UAV classification with respect to the mission, vehicle performance, (range, altitude, endurance), the type of payload and the launch and recovery requirements. Problems related to "Airspace Policy and Air Traffic Management" were the subject of the second lecture. These are challenges for which effective solutions are urgently required in the next few years, especially in Europe where the airspace is already very crowded. The first day ended with a lecture on C3, highlighting the issues arising when the crew are removed from the aircraft.

The second day started with a lecture on "Tools for Optimization and Validation of System Architecture and Software", addressing the need for optimization and the techniques already available today. The lecture on "Design and Airworthiness Requirements for Unmanned Air Vehicle Systems" examined the safety implications and factors to be considered for the procurement of a UAV and identified the design requirements to be used as a guide to produce an air vehicle specification. Aspects of vehicle and payload control were dealt with during the lecture on "UAV Datalinks: Tasks, Types, Techniques and Examples".

On Wednesday a lecture was given on "The Developmental and Operational Challenges of UAV and UCAV Airbreathing Propulsion". Benefits, advantages and disadvantages of various types of UAV propulsion technologies were reviewed. Case histories on Pioneer, Predator and Global Hawk were presented. The afternoon was dedicated to micro aerial vehicles. A lecture entitled "Microflyers and Aerial Robots: Missions and Design Criteria" provided an overview of the issues surrounding the design and choice of appropriate missions for this class of unmanned flying vehicles.

"Aerodynamic Measurements at Low Reynolds Numbers for Fixed Wing Micro Air Vehicles" was the subject of a half day lecture given on Thursday. The results of a study of the methods that can be used to obtain reliable force and moment data on thin wings in wind and water tunnels were presented as well as balance characteristics and validation. During the lecture on "Tactical Payloads for UAVs" various imaging and non-imaging sensors were described.

On Friday the main subject of the lecture on "Various sensors aboard UAVs" was Synthetic Aperture Radar (SAR). The working principles, challenges and future developments of this complex imaging sensor were translated into understandable words for observers not familiar with the subject. The lecture on "Use Case Analysis and the Formulation of Functional Requirements for Complex Systems: A Case Study for UAVs" gave an example on how modern mathematical tools can be applied for the elaboration of a Request for Proposal (RFP). Finally, the last lecture entitled "The B-Hunter UAV System" illustrated some modifications and upgrades of the Hunter UAV to fulfill the requirements of the RFP issued by the Belgian Army.

Développement et utilisation des avions sans pilote (UAV) pour des applications civiles et militaires

(RTO EN-9)

Synthèse

Ce cours spécial international a rassemblé 60 ingénieurs et scientifiques (47 observateurs et 13 conférenciers) ressortissants de 14 pays différents pour une période de cinq jours, du 13 au 17 septembre 1999.

Le premier cours, «Les UAV, tour d'horizon de la situation actuelle et perspectives d'avenir» a mis l'accent sur la classification des UAV par rapport à la mission, aux performances (portée, altitude, endurance), au type de charge utile et aux besoins en matière de lancement et de récupération. Les problèmes relatifs à «La politique de gestion de l'espace aérien et la gestion du trafic aérien» ont fait l'objet du deuxième cours. Il s'agissait des défis pour lesquels des solutions efficaces doivent être rapidement trouvées au cours des prochaines années, surtout en Europe où l'espace aérien est déjà très encombré. Le premier jour s'est achevé par un cours sur le C3 qui a mis en relief les problèmes qui se posent dès qu'il est fait abstraction de l'équipage.

La deuxième journée a débuté par un cours sur «Les outils d'optimisation et de validation des architectures et des logiciels des systèmes» qui a souligné le besoin d'optimisation, ainsi que les techniques déjà disponibles. Le cours sur «Les spécifications de conception et d'aptitude au vol des systèmes UAV», a ensuite examiné les conséquences pour la sécurité et les facteurs à prendre en considération lors de l'achat d'un UAV. Les spécifications de conception à suivre lors de l'établissement des spécifications techniques d'un véhicule aérien ont été décrites. Enfin, certains aspects du contrôle des véhicules et de leurs charges utiles ont été traités lors du cours sur «Les UAV et les liaisons de données : Tâches, types, techniques et exemples».

Le mercredi, un cours a été donné sur «Les défis liés au développement et à l'utilisation opérationnelle de la propulsion aérobie des UAV et UCAV». L'intérêt, les avantages et les désavantages de différents types de technologies de propulsion pour UAV ont été étudiés. Des études de cas concernant les Pioneer, Predator et Global Hawk ont été présentées. L'après-midi a été consacré aux micro-véhicules aériens. Une communication intitulée «Les micro-avions et les robots aériens : Missions et critères de conception» a fait un tour d'horizon des questions d'actualité concernant la conception et le choix de missions appropriées pour cette catégorie de véhicules aériens sans pilote.

«Les mesures aérodynamiques aux faibles nombres de Reynolds pour les micro-véhicules aériens à voilure fixe» a été le sujet d'un cours d'une demi-journée le jeudi. Les résultats d'une étude sur les méthodes d'obtention de données fiables sur les forces et les moments exercés sur les voilures minces en soufflerie et en tunnel hydrodynamique ont été présentés, ainsi que les caractéristiques de centrage et leur validation. La communication sur «Les charges utiles tactiques pour UAV» a décrit différents types de capteurs d'images et autres.

Le vendredi, les radars à synthèse d'ouverture SAR ont été le principal sujet de la communication sur «Les différents capteurs embarqués sur UAV». Les principes de fonctionnement, les défis et le développement de ce capteur complexe ont été exprimés d'une manière claire et compréhensible même pour l'observateur inexpérimenté. La communication sur «L'analyse des cas d'utilisation et la définition des caractéristiques fonctionnelles des systèmes complexes : Une étude de cas pour les UAV» a présenté un exemple de mise en oeuvre d'outils mathématiques modernes pour l'élaboration d'un appel d'offre (RFP). Enfin, la dernière communication sur «Le système UAV B-Hunter», a illustré certaines modifications et améliorations apportées à l'UAV Hunter afin de répondre aux exigences du RFP émis par l'armée Belge.

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UAVs — CURRENT SITUATION AND CONSIDERATIONS FOR THE WAY FORWARD

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The opinions expressed in this document are those of the author and do not necessarily reflect those of EURO UVS.

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.

This document will try to give the reader an overview of the current situation pertaining to unmanned aerial vehicle (UAV) systems in the world and it is will endeavour to give some indications on what the future may have in store for us. It does not have the pretention of being complete and covering everything going on in this field in every country, but rather it will try to give a representative overview of the UAVs currently in use, being considered for purchase and the general state of UAV-related technology and the industry involved.

PREAMBLE & DEFINITION

At the onset, it is considered worthwhile to try to define what is meant by the term UAV, therewith hopefully avoiding any misunderstandings.

> **UAVs are to be understood as uninhabited and reuseable motorized aerial vehicles, which are remotely controlled, semi-autonomous, autonomous, or have a combination of these capabilities, and that can carry various types of payloads, making them capable of performing specific tasks within the earth's atmosphere, or beyond, for a duration, which is related to their missions.**

This broad definition permits to encompass fixed and rotary wing UAVs, lighter-than-air UAVs, lethal aerial vehicles (training rounds without warheads), aerial decoys, aerial targets, alternatively piloted aircraft and uninhabited combat aerial vehicles, therewith highlighting the fact that these systems have a certain number of common features, offer the potential for cross-over technology, and utilize or will utilize similar technologies.

However, the separation line with cruise missiles is not really clear; indeed, it has been argued that cruise missiles are actually UAVs. This overview will not include cruise missiles, and will only sideways refer to aerial target vehicle systems.

The classification and abbreviations indicated in Figure I, will be used and referred to in this document. Range, as indicated in Figures I and II should be understood as the operational range (LOS and/or SAT/COM) of the uplink (command & control) and downlink (telemetry & imagery). There are a number of other parameters, such as flight altitude, launch & recovery methods, that can be used to further classify UAVs. For purposes of clarity, the classification of Special Task UAVs has been added.

Figure I — UAV CLASSIFICATION

CATEGORIES	ABBR.	RANGE km	FL. ALT. m	ENDURANCE hours
TACTICAL UAVs				
Micro	μ	< 10	250	1
Mini	MINI	< 10	350	< 2
Close Range	CR	10 - 30	3.000	2 - 4
Short Range	SR	30 - 70	3.000	3 - 6
Medium Range	MR	70 - 200	3/5.000	6 - 10
MR Endurance	MRE	> 500	5 - 8.000	10 - 18
Low Altitude Deep Penetration	LADP	> 250	50 - 9.000	0,5 - 1
Low Alt. Endurance	LAE	> 500	3.000	> 24
Medium Altitude Long Endurance	MALE	> 500	5 - 8.000	24 - 48
STRATEGIC UAVs				
High Altitude Long Endurance	HALE	> 1000	15 - 20.000	24 - 48
Uninhabited Combat Aerial Vehicles	UCAV	+/- 400	< 20.000	+/- 2
SPECIAL TASK UAVs				
Offensive	LETH	300	3 - 4.000	3 - 4
Decoys	DEC	0-500	50 - 5.000	up to 4

A general review, taking the aforementioned into account, and supplying examples in each category, can be found in Figure III.

GENERAL SITUATIONAL OVERVIEW

Up to now, funding for the development of UAVs has principally been put up by the military and this is expected to remain so for the foreseeable future. Eventhough UAVs have been around, in one form or another for nearly 50 years, their military value and complementarity in relation to other weapon systems has, until recently, not been generally acknowledged and accepted by the military hierarchy and the political establishment until fairly recently.

The successful deployment of UAVs during the Gulf War was instrumental in making the international military hierarchy conscious of the actual merits of UAVs and the various roles they could be used for. Thanks to CNN, it was also the first time that the use of UAVs was brought to the attention of the politicians and the general public. During this conflict, tactical UAVs were deployed (Exdrone/USA, Pointer/USA, Pioneer/USA, Mart/France) and tactical decoys were used (Chukar/USA & TALD/Israel, both by the USA). The Phoenix UAV (GEC-Marconi) was sent to the Gulf, but did not make it in time to be deployed before the end of the conflict.

The more recent and successful deployments of UAVs over Bosnia and Kosovo (CL289 by France & Germany; Pheonix by UK; Hunter, GNAT, Pioneer and Predator by USA) have greatly contributed to the wider acceptance and recognition of the value of UAVs.

It is commonly stated that UAVs are used for missions that are «dull, dirty and dangerous». This refers to missions which would generally be long, tiring, and in some cases boring, for aircraft pilots, and which would present a high risk factor for pilots. After initial grumblings by air force personnel, the use of UAVs is increasingly being considered as complementary to missions by piloted aircraft. This has resulted in the recognition and acceptance of the value of UAVs by pilots, which has without any doubt positively contributed to the development of medium and high altitude (MALE & HALE) UAVs. These UAV systems can be used for surveillance or treaty monitoring purposes, as well as battle damage assessment, over hostile and heavily defended areas, where a downed

Figure II — UNINHABITED AERIAL VEHICLE SYSTEM CLASSIFICATION

TACTICAL											STRATEGIC		
LETH	Decoy	Micro	Mini	CR	SR	MR	MRE	LADP	MALE	LAE	UCAV	HALE	
		X	X	X	X	X							Rotary Wing
X	X	X	X	X	X	X	X	X	X	X	X	X	Fixed Wing
		X	X	X	X								Light-Than-Air
					X	X		X	X	X	X	X	Optionally Piloted
Hand-, Weapon-, Air-launched, Launcher, VTOL, RATO											Wheels		Launch Method
		Skids, Net, Parachute (+ Airbags), VTOL, Wheels								Wheels			Recovery Method

pilot would not only risk his own life, but could also risk the lifes of the extraction team, or, if caught, could even become a political liability to the government of his country, or the alliance his country is a member of.

In many cases, the development of UAVs has been hampered by ever-changing military requirements, which resulted in them being forced to fulfill multiple roles. The problems encountered by the money guzzling US Aquila and Outrider programmes can be traced back to this problem. It is now recognized that it is impossible to produce a single UAV that can fulfill all roles. Most UAVs in operation today still reflect a large degree of «customized uniqueness», which can be linked to the system's first customer, and restricts the system's potential with another military customers.

Military forces are now mostly considering families of complementary UAVs in both the tactical and the strategic categories, with the Army in most cases responsible for tactical and the Air Force for the strategic assets. With the advent of VTOL UAVs, the Navy is also starting to show keen interest. However, a special mention should be made of the experience AAI Corp., USA has in the field of ship-launched (RATO) fixed wing UAVs. AAI Corp. has been involved with the Pioneer UAV from the onset, and has not only been responsible for the majority of the very many upgrades that have been made of the years, but also gained valuable operational experience during the Gulf War, when they established a forward base in Bahrain from where they serviced and reconditioned Pioneer UAVs, which were extensively launched from land-based bases, as well as from ships. Their ship-launch experience with Pioneer has made it possible for AAI Corp. to develop, within a very short period of time, in reply to a requirement of the South Korean Navy, the fixed wing Shadow 400 (range: 200 km), which is ship-launched (by means of RATO) and ship-recoverable (by means of a recovery net on the rear deck).

Today, there is a clear tendancy to develop UAVs directed at fulfilling specific missions. Specialization is the name of the game. This however does not always mean that totally new systems have to be developed. There is a clear trend towards to making UAVs modular: by changing payloads, the same aerial vehicle can fulfill another function. This however sounds easier than it is.

VTOL UAVs are currently being looked at for airborne (military & humanitarian) mine detection purposes (France, Germany, Netherlands, UK, USA) on land and in the littoral area, as well as for urban warfare roles, perimetric surveillance purposes, helicopter flight path reconnaissance, and UGV command and control relay.

The arrival of shipborne VTOL UAVs is starting to be seen on the horizon; these systems will most probably be initially deployed in the USA, where the US NAvy conducted a technology maturity evaluation in 1998, which continues in its second phase in 1999. It should be noted that there is a clearly defined future requirement for shipborne VTOL UAVs for various roles on upcoming new generation NATO frigates.

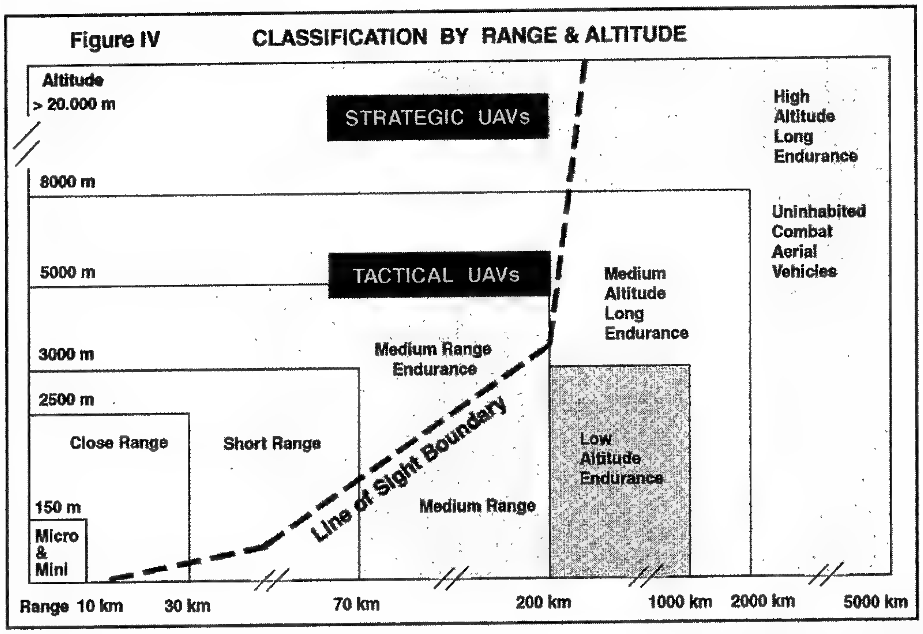
Interest in VTOL aerial targets capable of realistically simulating popping up attack helicopters (for weapon system evaluation and AAA training) is also growing, as is manifested by Bristol Aerospace's Hokum-X programme with the US Army Targets Management Office.

VTOL UAVs are also being used for an ever-growing number of civilian applications. Japan has been extremely active in agricultural applications; well over a

	RANGE	ENDURANCE	FLIGHT ALT. (Max)	LAUNCH METHOD	RECOVERY METHOD
Category	kms	hours	meters		
		TACTICAL UAVS			
MICRO µ	< 10	< 1	250	By Hand H-HL, WL VTOL +	Belly, skids
Missions Examples	RSTA, comms relay, scouting, NBC sampling, EW MicroStar, Hyperav+, Black Widow, Microbat				
MINI	< 10	< 2	350	H-HL, L VTOL + Wheels	Belly, skids Wheels Parachute
Missions Examples	Film industry, broadcast industry, agriculture, pollution measurement, powerline verification, mine detection Aerocam, RPH2+, R50+, RMax+, SurveyCopter				
CR	10 - 30	2 - 4	3000	H-HL, L VTOL + Wheels	Belly, skids Wheels Parachute
Missions Examples	Recon, EW, artillery correction, mine detection, crop survey, search & rescue APID+, Camcopter+, Cypher+, Dragon/Exdrone, Javelin, LUNA, Mini-Tucan, Backpack, Observer, Pointer, Vigilant, Vigiplane				
SR	30 - 70	3 - 6	3000	L VTOL + RATO	Belly-skids Parachute Para/airbag
Missions Examples	RSTA, BDA, EW, NBC sampling, mine detection, wildlife research, mineral prospection Crecerelle, Dragon, EyeView, Fox, Heliot+, Mirach 26, Nishant, Phantom, Phoenix, Sentry, Sojka, Vulture				
MR	70 - 200	6 - 10	3 - 5000	L, VTOL + Wheels RATO	Skids Wheels Para/airbag
Missions Examples	RSTA, BDA, artillery correction, EW, NBC sampling, mine detection, comms relay Brevel (KZD), CL327+, Eagle Eye+, Hunter B, Mücke, Outrider, Pioneer, Prowler, Ranger, Searcher, Seeker, Shadow 200, Shadow 400, SkyEye, Sniper, Sperwer				
MRE	1000	10 - 18	5/8000	Wheels RATO	Wheels
Missions Example	RSTA, BDA, comms relay Hermes 450S, Prowler II, Searcher II, Shadow 600, S.Vultre				
LADP	> 250	0,5 - 1	50 - 9000	RATO	Para/airbag
Missions Examples	Recon CL89, CL289, Mirach 100, Mirach 150				
LAE	> 500	> 24	3000	Wheels Launcher °	Wheels Para/airbag
Missions Examples	Meteorological sensing Aerosonde °, Laima, Pelican (Optionally piloted aircraft)				
		OFFENSIVE UAVs			
LETHAL	300	3- 4	3 - 4000	Launcher RATO Air-launch •	Expendable
Missions Examples	Anti-tank/vehicle, anti-radar, anti-infrastructure, anti-ship Harpy, K100, Lark, Marula, Polyphem, Taifun, Sea Ferret •				
MALE	500-750	24 - 48	5 - 8000	R-L.G.	R-L.G.
Missions Examples	RSTA, BDA, comms relay, EW, weapons delivery Altus, Hermes 1500, Heron (EagleStar), I.GNAT, Perseus, Predator, Theseus				
		STRATEGIC UAVS			
UCAV	+/- 400	+/- 2	< 20.000	Wheels	Wheels
Missions	SEAD, Air-to-air combat				
HALE	1 - 6000	24 - 48	15-20.000	R-L.G.	R-L.G.
Missions Examples	RSTA, BDA, comms relay, EW, boost phase intercept missile launch vehicle Darkstar, Global Hawk, Raptor, Condor				
		DECOYS			
DECOYS	0 - 500	a few min. to several hours	50 - 5000	Canister * RATO Air-launch	Expendable
Missions Examples	Aerial & naval decoys Chukar, Delilah, Flyrt, MALD, Nulka *, TALD				

EXPLANATIONS

H : Hand-launched
H-HL : Hand-held launcher
L : Launcher W : Wheels
VTOL : Vertical Take-Off & Landing
RATO : Rocket assisted Take-Off
RSTA : Recon, Surveillance, Target Acquisition
EW : Electronic Warfare
BDA : Battle Damage Assessmt
R-L.G. : Retractible landing gear



manouevre against or around them, and conduct battle damage assessment, or with the advent of foilage penetrating radar, see through multiple canopy jungles. They are the ideal tool in the rapidly moving battlefield of the end of the 20th and the beginning of the 21st century. The air-transportability of most UAV systems makes them rapidly deployable to mission staging areas all around the world.

UAVs with limited performance capabilities are relatively easy and inexpensive to produce, using readily available commercial off-the-shelf components,and because an evergrowing number of countries are deploying or trying to deploy them UAVs are now being recognized by NATO and most advanced countries as a serious threat, against which its forces have to be trained. This fact explains the upcoming requirement with the US Army for aerial targets capable of realistically simulating specific UAVs, as well as the emerging interest in low-cost simple UAVs with limited imagery capabilities to be used to train the soldior in the field to constantly be on the alert for UAVs.

2000 VTOL UAVs (all produced in Japan) and with payload capabilities varying from 25 to 150 kg, have been sold for crop spraying, fertilizing and seading purposes in Japan. There are over 4500 licenced commercial UAV operators in Japan. South Korea is now also producing a VTOL UAV for agricultural applications.

When one considers the combined use of various UAVs by NATO nations, interoperability (operating different UAVs in the same theatre of operations, operating different UAVs through the same ground control station and/or receiving data different UAVs at non-system specific terminals) rapidly becomes an issue. Joint intervention and peacekeeping or treaty monitoring operations within a UN- or NATO-instigated coalition are other drivers in this direction and are making their influence felt in the area of command & control and datalink (frequency) standardization, which is being addressed by a number of NATO agencies, commitees and working groups.

Currently, UAVs are principally being tasked with surveillance & monitoring, target location, reconnaissance and battle damage assessment. In most cases, UAVs are only as good as the payloads they carry. Tremendous technological advances have been made in this area over the last few years. Imaging payloads are getting ever smaller and more powerful and all-weather capability is finally becoming a reality. Synthetic aperture radars (SAR) are starting to become operational (TSAR on Predator, HISAR on Global Hawk) and are being downsized to be able to fit into tactical UAVs (SWORD programme for the CL289; Lynx development for Prowler II). Various types of payloads for chemical and biological sensing are being experimented with; airborne land and sea mine detection sensors, as well as various EW packages are also under development in various countries.

It is increasingly clear that UAVs will be, and in some cases already are, a critical part in the military information chain. They are emerging as the next generation of airborne reconnaissance, thanks to their ability to penetrate enemy airspace and dwell over or near target areas, and detect, identify, and track hostile activity in sufficient time to target lethal weapon systems or

Autonomous offensive UAVs with radiation seeker heads, such as the Harpy (IAI, Israel), K100 (CAC Systèmes, France), Lark (Kentron, South Africa) could start to experience increased demand due to the requirement to defeat ever more sophisticated air defence radars. One of the largest European UAV development contracts recently awarded was for the Taifun offensive UAV (STN Atlas Elektronik, Germany), which, equipped with a radar-based seeker head (Dornier, Germany) and an automatic onboard target recognition capability, is being developed to attack vehicles, strategic structures, as well as radar sites.

The commercial use of UAVs could have a beneficial effect on the use of military UAVs, as economies of scale would then become possible in certain areas. The commercial use of UAVs is not only being severely limited by air traffic management issues and high acquisition costs, but also by the high price of ownership and insurance (in relation to manned aircraft). The high cost of insurance severely limits the interest of leasing UAV systems for commercial (or military applications). The excessive cost of insurance is generally attributed to the unproven reliability (safety) of UAVs; once UAV technology has proven itself a little more, and acceptable UAV system qualification norms exist, their cost should come down.

The attrition rates for UAVs (all categories) are still relatively high in comparision with those of manned aircraft, and weigh rather heavily on the system's operational cost. Most UAV mishaps tend to occur during the launch and recovery phases. This in turn, is motivating authorities to increasingly specify automatic launch (take-off) and recovery systems for their future

requirements.

Dual redundancy is becoming more common, and in some cases, is already being imposed by the military customers.

UAV and payload operator training is currently still principally accomplished by flying. This will have to change and simulator-based training will without any doubt become more and more important. However, the few training simulators that exist are principally system specific (and therefore expensive) and do not permit the training of operators for various other types of UAV systems. Simulator training is bound to be cheaper, increase operation proficiency, without the material risks associated with flying (attrition), and will be totally independant of weather conditions and the current restrictions imposed by the air traffic management authorities.

The commercial use of UAVs is still in its infant shoes and principally concerns small and very short range VTOL UAVs and lighter-than-air (dirigible) UAVs, which are flown in-sight (motion picture industry, TV broadcasting of sports events, rock concerts, filming of publicity shots & video clips); as an exception, mention should be made of the rather large VTOL UAVs coming on the market in Japan for agricultural applications.

However, interest in using UAVs is growing within the scientific world, as is witnessed by the Australian/US Aerosonde meteorology programme, and the Swedish WITAS programme concerning the development of a fully autonomous VTOL UAV system with rational decision making capabilities for, amongst others, traffic surveillance tasks, NASA's Environmental Research Aircraft & Sensor Technology (ERAST) research programme using the Altus UAV, and the establishment of CIRPAS (Center for Interdisciplinary Remotely Piloted Aircraft Studies) in Monterey, CA, by the US Office of Naval Research, with the purpose to provide UAV flight services to support research. A special mention can be made of the study being undertaken by the Baltic states relative to the use of a high flying long endurance UAV, which would be used to relay command & control uplinks to, as well as imagery downlinks, from lower flying smaller UAVs deployed by the participating countries around the Baltic Sea for various purposes, such search & rescue (SAR), and maritime pollution control.

Telecommunications and pay-for-what-you-watch TV companies are investigating the use of very long endurance UAVs as «surrogate low altitude satellites» for relay purposes; this type of UAV application could find a market not only in industrialized nations, but could also help bring modern telecommunications to lesser developed countries. China has expressed keen interest in such systems.

PRINCIPAL UAV MANUFACTURERS

Figure V gives an overview of the world's principal current UAV manufacturers. Due to the limits imposed by what can legibly be put on a single page, this table does not mention manufacturers of lighter-than-air UAVs (which are mentioned separately), nor aerial targets and decoys; however some reference is made to the latter in this document.

Figure V indicates UAV manufacturers alphabetically by country, designating their UAV systems by name, and detailing the type of airframe (fixed or rotary wing, high speed small wing), UAV class (tactical or strategic), UAV category (micro, mini, close range, short range, medium range, low altitude deep penetration, medium range endurance, low altitude endurance, medium altitude long endurance, high altitude long endurance, offensive), and UAV application.

High speed small wing airframes are to be understood as cylindrical fuselages with stub-wings and in some cases canards or foreplanes, which are launched from zero-length launchers by means of RATO (CL289) or air-launched (Mirach 150).

UAV INDUSTRY

The principal UAV system manufacturers (current & potential) can be devided into two categories:

A- Major Defence Manufacturers

(UAVs are **NOT** core technology)

- Aérospatiale Matra, France ♦
- Alliant Techsystems, USA
- Bell Helicopter Textron, USA
- Boeing, USA
- British Aerospace, UK
- Dassault Aviation, France
- Dawoo Heavy Industries, South Korea
- DaimlerChrysler Aerospace (DASA), Germany
- ENICS, Russia
- Fuji Heavy Industries, Japan
- GEC-Marconi, UK (now BAe)
- Kawada Industries, Japan
- Kaman Aerospace, USA
- Kamov, Russia ♦
- Matra BAe Dynamics, France & UK
- Northrop Grumman, USA ♦
- Oerlikon-Contraves, Switzerland
- Raytheon, USA
- Saab, Sweden
- SAIC, USA
- Sikorsky Aircraft, USA
- Sokol, Russia
- Teledyne Ryan Aeronautical, USA ♦
- Thomson-CSF Detexis, France
- TRW, USA
- Tupolev, Russia ♦
- Turkish Aerospace Industries, Turkey ♦
- Yakovlev, Russia
- Yamaha Motor Company, Japan
- Yanmar, Japan

B- UAV System Manufacturers

(UAVs **ARE** core technology)

- AAI Corp., USA
- Aerosonde Robotic Aircraft, Australia
- AeroVironment, USA
- ATE, South Africa
- BAI Aerosystems, USA
- Bombardier-Canadair, Canada
- CAC Systèmes, France ♦
- Dornier (DASA), Germany
- EES, Turkey
- EMT, Germany
- General Atomics Aeronautical Systems, USA
- Insitu Group, USA
- Israeli Aircraft Industries, Israel
- Kentron, South Africa ♦
- Meteor, Italy ♦
- Mission Technologies, USA
- Pioneer UAV Inc., USA
- Sagem, France
- Techno-Sud Industries, France

Figure I **Overview Of Current UAV System Manufacturers (excluding aerial targets & decoys)**

COUNTRY	MANUFACTURER	SYSTEM	AIRFRAME		CLASS		CATEGORY	APPLICATION
Australia	Aerosonde Robotic Aircraft	Aerosonde	FW				LAE	Meteorology & research
	British Aerospace Australia	Nulka		VTOL	Tactical		Decoy	Decoy
Austria	Schiebel Elektron. Geräte	Camcopter		VTOL	Tactical		CR	RSTA, mine detection
Brazil	Gyron Sistemas Autonomos	Helix		VTOL	Tactical		CR	RSTA
Canada	Bombardier-Canadair	CL327 & 427		VTOL	Tactical		MR	RSTA, comms relay
Czech Republic	VTUL a PUL	Sojka III	FW		Tactical		SR	RS
France	Aérospatiale Matra	CL289	HSSW		Tactical		LADP	RS
		Hussard	FW		Tactical		CR	FOG RSTA
	Altec Industries	S-Mart	FW		Tactical		SR	RSTA
	CAC Systèmes	Fox AT & TX	FW		Tactical		SR	RSTA
		K100	FW		Tactical		LETH	Anti-vehicle & structure
	(in coop. w EDT & Dragonfly)	Heliot		VTOL	Tactical		SR	RSTA
	Envol Images	unnamed		VTOL	Tactical		MINI	Commercial
	Matra BAe Dynamics	Dragon	FW		Tactical		SR	EW
	Sagem	Crecerelle	FW		Tactical		SR	RSTA & EW
		Marula	FW		Tactical		LETH	RSTA & EW
		Sperwer	FW		Tactical		MR	RSTA
		Ugglan	FW		Tactical		MR	RSTA
	SurveyCopter	SurveyCopter		VTOL			MINI	Commercial
	Techno-Sud Industries	Vigilant 2000		VTOL	Tactical		CR	RS
		Vig.-Fuji 5000		VTOL	Tactical		MR	RSTA
		Vigiplane	FW		Tactical		CR	RS
	Thomson-CSF	Camcopter		VTOL	Tactical		CR	RSTA, mine detection
Germany	Dornier	CL289	HSSW		Tactical		LADP	RS
		Seamos		VTOL	Tactical		SR	RSTA, comms relay
	EMT	Luna	FW		Tactical		CR	RS
	STN Atlas Elektronik	KZO & Tucan	FW		Tactical		MR	RSTA
		Taifun	FW		Tactical		LETH	Anti-vehicle & anti-structure
		Mücke	FW		Tactical		MR	EW
		Mini-Tucan	FW		Tactical		CR	RSTA
Greece	3 Sigma	Nearchos	FW		Tactical		SR	RSTA
International Cooperation	- Matra BAe Dyn./France & STN Atlas Elektron./Germany	Brevel (KZO)	FW		Tactical		MR	RSTA
	- AAI/USA & IAI/Israel	Pioneer	FW		Tactical		SR	RSTA
	- TRW/USA & IAI/Israel	Hunter	FW		Tactical		MR	RSTA
	- ES&S/Austral. & Insitu/USA	Aerosonde	FW				EN	Meteorology & research
	- Eagle, Belgium & IAI, Israel	Hunter B	FW		tactical		MR	RSTA
	- Matra BAe Dyn. & IAI, Israel	Eagle Star	FW			Strategic	MALE	RSTA
India	ADE, Bengalore	Nishant	FW		Tactical		SR	RSTA
Israel	Israeli Aircraft Industries	Scout	FW		Tactical		SR	RSTA
		Searcher II	FW		Tactical		MRE	RSTA
		Harpy	FW		Tactical		LETH	Anti-radar
		Heron	FW			Strategic	HALE	RSTA
	Silver Arrow	Micro-V	FW		Tactical		SR	RS
		Sniper	FW		Tactical		MR	RSTA
		Hermes 450S	FW		Tactical		MRE	RSTA
		Hermes 1500	FW			Strategic	HALE	RSTA
Italy	Meteor (Alenia)	Mirach 20 & 26	FW		Tactical		SR	RSTA
		Mirach 100 & 150	HSSW		Tactical		LADP	RS
Japan	Fuji Heavy Industries	RPH2		VTOL	Tactical		MINI	Agriculture
	Kawada	RoboCopter 300		VTOL	Tactical		MINI	Agriculture
	Kubota Co.	KG200		VTOL	Tactical		MINI	Agriculture
	Yamaha Motor Co.	R50, R-Max		VTOL	Tactical		MINI	Agriculture
	Yanmar Agricult. Equipment	KG135II, YH300		VTOL	Tactical		MINI	Agriculture
South Africa	ATE	Vulture	FW		Tactical		SR	Artillery correct.
		Super Vulture	FW		Tactical		MRE	RSTA, EW
	Kentron	Seeker	FW		Tactical		MR	RSTA
		Lark	FW		Tactical		LETH	Anti-radar
South Korea	Daewoo	Bijo	FW		Tactical		MR	RSTA
		Arch 50		VTOL	Tactical		MINI	Agriculture
Sweden	Scandicraft Systems	Apid		VTOL	Tactical		SR	RSTA, EW
	Techment	RPG MK I, II, III		VTOL	Tactical		SR	RSTA
Switzerland	Oerlikon-Contraves	Ranger	FW		Tactical		MR	RSTA
Turkey	EES	Kirlangic	FW		Tactical		SR	RSTA
		Dogan	FW		Tactical		MR	RSTA
UK	Airspeed Airships	AS-100, 400, 600		L-t-A			MINI	Commercial
	Intora-Firebird	Firebird		VTOL	Tactical		SR	various
	Flight Refueling	Raven	FW		Tactical		SR	RSTA
	GEC-Marconi	Phoenix	FW		Tactical		SR	RSTA
	Meggitt Aerospace	Phantom	FW		Tactical		CR	RS
		Spectre	FW		Tactical		SR	RSTA
USA	AAI Corp	Shadow 200	FW		Tactical		SR/MR	RSTA
		Shadow 400	FW		Tactical		MR	RSTA
		Shadow 600	FW		Tactical		MRE	RSTA, comms relay
	AeroVironment	Pointer	FW		Tactical		CR	RS
	Alliant Techsystems	Outrider	FW		Tactical		MR	RSTA
	BAI Aerosystems	Exdrone/Dragon	FW		Tactical		SR	RS
		Javelin	FW		Tactical		CR	RS
	Bell Helicopter Textron	Eagle Eye		VTOL	Tactical		MR	RSTA, comms relay
	Boeing	Can. Rotor Wing		VTOL	Tactical		MR	RSTA
		Heliwing		VTOL	Tactical		MR	RSTA, comms relay
	Freewing Aerial Robotics	Scorpion		STOL	Tactical		MR	RSTA
	General Atomics	Altus	FW			Strategic	HALE	Research
		I. GNAT	FW			Strategic	MALE	RSTA
		Prowler II	FW		Tactical		MRE	RSTA
		Predator	FW			Strategic	MALE	RSTA
	In Situ Group	Laima	FW				LAE	Meteorology & research
	Lear Astronics	SkyEye	FW		Tactical		MR	RSTA
	Lockheed Martin/Boeing	Darkstar	FW			Strategic	HALE	RS
	Mission Technologies (Mi-Tex)	Backpack UAV	FW		Tactical			CR
	NASA/Scaled Composites	Raptor	FW			Strategic	HALE	Research/Offensive
	Northrop Grumman	Sea Ferret	FW		Tactical		MR	R, offensive
		BQM-74C Recce	HSSW		Tactical		MR	R
	Pioneer UAV Inc.	Pioneer	FW		Tactical		MR	RSTA
	SAIC	Vigilante		VTOL	Tactical		MR	RSTA, comms relay
	S-Tec	Sentry	FW		Tactical		SR	RS
	Teledyne Ryan Aeronautical	Global Hawk	FW			Strategic	HALE	S
		Scarab	HSSW		Tactical		MR	R
	United Technolog. Sikorsky	Cypher		VTOL	Tactical		SR	RSTA

EXPLANATION :
FW = Fixed Wing
VTOL = Vertical Take-Off and Landing
MALE = Medium altitude long endurance
HSSW = High speed small wing
LADP = Low Altitude Deep Penetration
CR = Close Range
LAE = Low Alt. Endur.
HALE = High altitude long endurance
RSTA = Reconnaissance, surveillance, target acq.
EW = Electronic warfare
SR = Short Range
MR = Medium Range
MRE = Medium Range Endurance
LETH = Offensive
RS = Recon/surveillance
R = Reconnaissance
S = Surveillance

- Silver Arrow, Israel
- S-Tec, USA
- Schiebel Elektronische Geräte, Austria
- STN Atlas Elektronik, Germany

It is of interest to note that a number of the aforementioned companies also produce unmanned aerial target vehicle systems (UATV)(see ♦). There are also manufacturers specializing in UATV systems (core technology), and which consequently master certain UAV-related technologies, such as:

- Advanced Electronic Systems, United Arab Emirates
- Bristol Aerospace, Canada
- Flight Refueling, UK (developed & produced the Raven UAV)
- Meggitt Aerospace, UK
- STN Atlas-3 Sigma, Greece
- Tracor, USA (Marconi North America)
- Tasuma (UK) Ltd, UK

FIXED WING UAVs

By far the largest number of current UAVs in all categories are fixed wing UAVs with a great variety of airframe configurations, including: high wing with twin booms & inverted V tail (Aerosonde-Aerosonde Robotic Aircraft, Australia & Shadow 200-AAI Corp., USA); high wing with twin booms and twin fin tail unit (Nishant-ADE, India; Pioneer-Pioneer UAV Inc., USA; Mirach 26-Meteor, Italy; Shadow 400 & 600-AAI Corp. USA), low wing with twin booms (Ranger-Oerlikon-Contraves, Switzerland), mid-mounted delta wing with twin outward-canted fins & rudders (Sperwer-Sagem, France), low-mounted delta wing without horizontal tail surfaces (Spectre-Meggitt, UK), low-wing monoplane without horizontal tail surfaces (Brevel/KZO-Eurodrone, France), shoulder-wing monoplane (Luna-EMT, Germany), mid-mounted wings with dorsal and ventral fins (Taifun-STN Atlas, Germany), pod-and-twin tailboom high wing monoplane (Hunter-TRW, USA & IAI, Israel); twin-wing monoplane with sweptback fin and rudder with T tailplane and ventral fin (Outrider-Alliant Techsystems, USA and Hellfox & Vixen-Mission Technologies, USA), shoulder-winged pod fuselage with single tailboom with inverted V tail (EyeView-IAI, Israel), high-winged monoplane with boom fuselage and T tail unit (Raven-Flight Refueling, UK & Fox MLCS-CAC Systèmes, France & Vulture-ATE, South Africa & XRAE-DERA, UK), mid-wing double delta with endplate fins (Lark-Kentron, South Africa), parasol monoplane with pylon-mounted wing with pod and boom fuselage and T tail (Pointer-AeroVironment, USA), semetrical delta wing with single fin and rudder (Exdrone & Dragon-BAI Aerosystems, USA), pod fuselage with inboard wing stubs & outboard freewings and articulated twin tailbooms (Scorpion-Freewing Aerial Robotics, USA), low-wing monoplane with inverted V tail (Altus, GNAT, I.GNAT, Prowler, Predator (General Atomics, USA), high-winged delta with twin tailbooms with vertical tail surfaces bridged by double T tailplane (Sentry-S-Tec, USA). Fixed wing UAVs can have pusher engines, puller engines or both.

There is a relative small number of twin-engined UAVs: Dogan, Firefly and Krilangic (EES, Turkey), Hunter-(TRW, USA & IAI, Israel), Micro V and Hermes 450 & 1500 (Silver Arrow, Israel), Theseus (Aurora Flight Sciences, USA).

VERTICAL TAKE-OFF & LANDING UAVs

There is a constantly growing number of VTOL UAV producers and development programmes. There are currently more than thirty five companies in forteen countries involved with the production and/or development of more than forty six different VTOL UAVs. The principal manufacturers include: Bell Helicopter Textron in the USA, Bombardier Services in Canada, Dornier in Germany, Schiebel Elektronische Geräte in Austria, Sikorsky Aircraft in the USA, and Techno-Sud Industries in France. The Swedish company Techment has developed the cost-effective RPG, which is a gyroplane UAV. But by far the majority of the VTOL UAVs currently produced in the world are Japanese (Fuji, Kawada, Kubota, Yamaha, Yanmar) and are used in Japan for agricultural purposes.

The following companies produce, and in some cases specialize, in VTOL UAVs, or have rotary wing UAVs in development:

Manufacturer	***VTOL Designation***
- Adv. Aerospace Techn., USA	Spinwing
- AeroCam, USA	23F & 60F
- BAeAustralia, Australia	Nulka
- Bell Helicopter Textron, USA	Eagle Eye
- Boeing, USA	Canard Rotor/Wing
- Bombardier-Services, Canada	CL327
- CAC Systèmes, France	Heliot
- Daewoo Heavy Ind., S.Korea	Arch 50
- Dornier, Germany	Seamos
- Dragonfly Pictures, USA	DP-4
- Frontier Systems, USA	A160 Hummingbird
- Fuji Heavy Industries, Japan	- RPH-1 & 2 - Fuji 5000
- Gyros Sistemas Autons, Brazil	Helix
- Intora-Firebird, UK	Firebird
- Kaman Aerospace, USA	K-Max
- Kamov, Russia	KA-37 & KA-137
- Kawada Industries, Japan	Robocopter300
- MovingCam, Belgium	FlyingCam
- Orion Aviation, USA	Seabat 706
- SAIC, USA	Vigilante
- Scandicraft Systems, Sweden	APID
- Schiebel Elektr. Geräte, Austria	Camcopter
- SurveyCopter, France	SurveyCopter
- Techno-Sud Industries, France	Vigilant 2000 Vigilant 5000
- Techment, Sweden	RPG (gyroplane)
- Yamaha Motor Comp., Japan	R50 & R-Max
- Yanmar, Japan	KG35 & 135 YH300

LIGHTER-THAN-AIR UAVs

There is a slowly growing number of development programs in the field of lighter-than-air UAVs. These UAVs potentially have a military, as well as a civilian market. It could well be that commercial applications of lighter-than-air UAVs will be an earlier reality than for fixed and rotary wing UAVs. A limited number is already being used for commercial and scientific applications. Lighter-than-air UAVs are being developed and produced (see ♣) by the following:

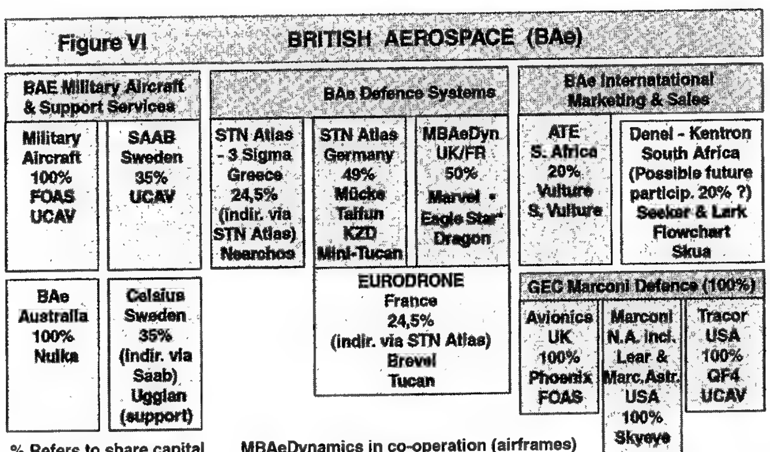
♣ - Advanced Hybrid Aircraft, USA	Hornet Hybrid RPB-35
♣ - Airspeed Airships, UK	AS-100 & 400 AS-600 & 800
- Automation Institute, Brazil	Aurora
- Aviation Industries China, China	FK-11 & 12

♣	- Bosch Aerospace, USA	Sass-Lite
♣	- Envol Images, France	El-4,5 & 10 & 15
	- Pan Atlantic Aerospace, USA	Leap
♣	- Promotional Ideas, UK	PIG 1 & 2 & 3
	- Shanghai Research Inst., China	Shen Zhou 1 & 2
♣	- Skypia, Japan	Mambow 4
	- Skysat Systems Corp., USA	
	- TCom, USA	32M & 71M
	- University of Stuttgart, Germany	Lotte 3

INDUSTRY CONSOLIDATION

The following examples clearly illustrate the current drive towards consolidation in the UAV-related industry:

- BAe, UK and Matra, France have teamed to form Matra BAe Dynamics on a 50/50 basis.
- BAe, UK (minority) & Rheinmetal, Germany (majority)jointly own STN Atlas Elektronik, Germany.
- STN Atlas Elektronik has purchased 50% of 3 Sigma in Greece. The new company is called STN Atlas-3 Sigma, and is positioning itself as a serious competitor for the NAMFI Range (Crete) aerial target requirement and should be well positioned for the upcoming Greek divisional level UAV requirement.
- BAe, UK has taken a 20% stake in ATE, S. Africa. This participation was taken well ahead of the announcement by South Africa's Ministry of Defence of the award of contract to BAe for the supply of Hawk training aircraft.
- Kentron and Advanced Technology & Engineering (ATE), both of South Africa, are laying the groundwork for a combined company, probably together with Denel Aviation, that could be announced shortly. It is anticipated that in order to maintain the level of its stake in ATE, BAe will have to increase its stake in the new South African entity.



% Refers to share capital controlled by BAe

MBAeDynamics in co-operation (airframes) with: • Freewing, USA
* IAI, Israel

- BAe, UK has taken a 35% stake in Saab, Sweden.
- BAe, UK has purchased the defence activities of GEC Marconi,UK, system integrator of the Phoenix UAV, and which includes Tracor, USA (purchased by GEC in 1998), as well as Marconi Astronics Inc, USA.
- Saab and the government owned Celsius Group in Sweden have announced the take-over of the Celsius Group by Saab. The name of the new company is not yet knwon. As 35% of Saab's share captial is owned by BAe, this will further increase BAe's international industrial base.
- EES, Turkey has purchased EAS, Israel, a developer and producer of various twin-engined UAVs.
- FLIR Systems, USA (producer of gyro-stabilized EO/IR imaging payloads) has acquired Agema, Sweden (producer of IR imagers), Polytech, Sweden (development & design of gyrostablized camera platforms), BSS, UK (former FLIR Systems distributor), and Inframetrics, USA (producer of EO/IR imaging payloads).
- Lockheed Martin, USA has acquired McDonnell Douglas, USA.
- Lockheed Martin, USA is in the process of taking over Teledyne Ryan Aeronautical, USA.
- Matra Hautes Technologies, France has taken over Aérospatiale; the combined group is now called Aérospatiale Matra.
- Matra BAe Dynamics, France is rumoured to be in the process of negotiating a take-over of CAC Systèmes, France.
- Meggitt Aerospace, UK has acquired TTL, UK (UATV & engines), Cartwright, USA (Doppler radar-based missed distance indicators), Hayes Targets, USA (tow targets), Sabre, UK (acoustic missed distance indicators), and South West Aerospace, USA (tow winches).
- Sagem, France has taken over the French optronics manufacturer SFIM and the French electronics firm SAT.
- Schreiner Aviation Group has created Schreiner Target Services Canada, which has purchased the target division from Bristol Aerospace, Canada.
- Thomson-CSF has purchased Dassault Electronique; the combined group is now called Thomson-CSF Detexis.

Israel has two totally independant UAV manufactuers (Israeli Aircraft Industries and Silver Arrow) with substantial expertise. Where IAI already has a number of co-operation agreements with the Eagle Consortium, Belgium (Hunter-B), Matra BAe Dynamics, France & UK (Eagle Star), Oerlikon-Contraves, Switzerland (Ranger), TRW & S-Tec, USA (Sentry), Silver Arrow is not known to have a teaming arrangement with a foreign industrial partner. In view of the high cost of development, one wonders how long this situation can last. One must also wonder how long it will be viable for two distinct UAV manufacturers to co-exist as separate entities in Israel, whose home market can obviously not warrant to keep both alive.

The recently announced amalgamation of Aérospatiale Matra, France and DaimlerChrysler Aerospace (DASA), Germany (EADS) is expected to make its presence felt in the UAV arena, but how and with what product is not really clear yet, unless the new group takes over an existing UAV manufacturer.

It can be concluded from the aforementioned that BAe has positioned itself as one of the major world players in the UAV arena, and definately the one with the widest international industrial base.

INDUSTRIAL COOPERATION

In order to be able to afford the investments required to bring a UAV system to maturity, or to overcome problems related to local content and in some cases offset commitments, industrial cooperation agreements (co-development and/or production) are starting to become more and more common on the international stage. To illustrate this point, the following examples are given:

Aerosonde	E.S. & S, Australia & Insitu Group, USA & Naval Research Laboratory, USA
Arch-50	Daewoo Heavy Industries, S. Korea & Kamov, Russia
Bijo	Daewoo Heavy Industries, S. Korea & AAI Corp., USA
Brevel	Eurodrone, a 50/50 joint venture between Matra BAe Dynamics (France & UK) and STN Atlas Elektronik, Germany
CL289	Bombardier-Canadair, Canada & Aérospatiale, France & DaimlerChrysler Aerospace, Germany
Crecerelle	Sagem, France & Meggitt Aerospace, UK
Darkstar	Lockheed Martin Skunk Works, USA & Boeing Military Aircraft Division, USA (continued development is stated to have been halted).
Eagle Eye	Bell Helicopter Textron, USA & Israeli Aircraft Industries, Israel & TRW, USA
Fox TX	CAC Systèmes, France & Thomson-CSF Detexis, France
Fuji 5000 Vigilant5000	Fuji Heavy Industries, Japan & Techno-Sud Industries, France
Global Hawk	Teledyne Ryan Aeronautical, USA & Lockheed Martin, USA & Raytheon Aircraft Co., USA
Heliot	Dragonfly, Italy & EDT, France & CAC Systèmes, France
Heron	Israeli Aircraft Industries, Israel & Matra BAe Dynamics, France & UK
Hunter	TRW Inc., USA & Israeli Aircraft Industries, Israel
Hunter B	Israeli Aircraft Industries, Israel Eagle Consortium, consisting of: - Sonaca, Belgium - Thomson-CSF Systems, Belgium - Thomson-CSF Electronics, Belgium - SAIT Systems, Belgium
Observer	Def. Evaluation Research Agency, UK & Cranfield Aerospace, UK & Tasuma (UK) Ltd, UK
Pioneer	Pioneer UAV Inc., a 50/50 joint venture between: AAI Corp., USA & Israeli Aircraft Industries, Israel
Ranger	Oerlikon-Contraves, Switzerland & Israeli Aircraft Industries, Israel & Swiss Aircraft Industries, Switzerland
RPG	Techment, Sweden & Army Intelligence School, Sweden
Shadow 600	AAI Corp., USA & Romanian company thru MoD
Siva	INTA, Spain & Ceselsa, Spain & DaimlerChrysler Aerospace, Germany
Spectre	Meggitt Aerospace, UK & Northrop Grumman, USA
UCAV/F-16	Lockheed Martin, USA & Tracor, USA
Vigilant5000	See Fuji 5000
Vigilante	SAIC, USA & Kawada, Japan

MARKETING ARRANGEMENTS

Teaming arrangements relative to the marketing of UAV systems in specific countries are becoming rather common, as is witnessed by the following examples:

Backpack	Mission Technologies, USA with Dornier (DASA), Germany - for marketing in selected countries.
Camcopter	Schiebel Elektronische Geräte, Austria with: Thomson-CSF Detexis Missiles - for marketing in France
Dragonfly	Dragonfly Sar, Italy, through their French distributor EDT, with: CAC Systèmes, France - for fitting the aircraft with an autopilot and marketing in selected countries.
Exdrone	BAI Aerosystems, USA with: Raytheon, USA - for competing for the US UAV target requirement.
Scorpion	Freewing Aerial Robotics, USA with: Northrop Grumman, USA - for the Tactical UAV competition in the USA with: Yamada International, Japan - for marketing in Japan
Marvel	Freewing Aerial Robotics, USA with: Matra BAe Dynamics, France - for marketing in France
Heron (Eagle Star)	Israeli Aircraft Industries, Israel with: Matra BAe Dynamics, France - for marketing in France & UK
Hunter B	Israeli Aircraft Industries, Israel with: the Eagle Consortium, Belgium - Sonaca, Belgium - Thomson-CSF Systems, Belgium - Thomson-CSF Electronics, Belgium - SAIT Systems, Belgium for marketing and production in Belgium
Pointer	Aerovironmet, USA with: CAC Systèmes, France - for marketing in Europe
Predator	General Atomics Aeronautical, USA with: Sagem, France - for marketing & logistical support in France with: Meteor, Italy - for marketing & logistical support in Italy with GEC-Marconi, UK - for marketing and logistical support in UK
Ranger	Oerlikon-Contraves, Switzerland with IAI, Israel - for marketing in Finland
Sentry	S-Tec, USA with TRW, USA and IAI, Israel - for marketing in the USA relative to the Tactical UAV programme
Skua (UATV)	Kentron, South Africa with Sagem, France - for marketing and logistical support in France
Vigilant	The airframe produced by Fuji Heavy Industries, Japan (Fuji 5000) and droned

by Techno-Sud Industries, France (TSI), is being marketed by TSI as Vigilant 5000 in Europe, Africa, Middle East and South America.

Vulture ATE, South Africa
with BAe, UK
- for marketing in selected countries.

CURRENT & UPCOMING UAV USERS

Figure VII gives an overview of the UAV systems in service, on order, or programmed in a sampling of countries around the world.

INTRODUCTION OF UAVs

The introduction of UAVs into the Armed Forces is a gradual process that is proceeding at different levels in different countries. Most of the industrialized world's military have firstly opted for tactical UAVs on a divisional level and are currently envisaging the introduction of strategic UAVs and/or regimental level tactical UAVs. The introduction of platoon level micro UAVs will start to follow in probably approximately five years (2005).

It should be mentioned that what is considered a regimental/brigade level system in one country, may be considered a divisional level system in another.

TACTICAL UAVs - Divisional Level

The first UAV wave to hit the world's defence forces principally concerned divisional level tactical systems. Such systems have been or are now in service, on order, are or have been under lease, or with Algeria, Australia, Belgium, Bulgaria, Czech Republic, Denmark, Egypt, Finland, France, Germany, India, Israel, Italy, Morroco, Netherlands, Romania, Russia, Singapore, South Africa, South Korea, Sri Lanka, Sweden, Switzerland, Thailand, Turkey, UAE, UK, USA. In nearly of of the aforementioned cases, the UAV systems are used for reconnaissance and surveillance, and in some cases also for target acquisition purposes.

Upcoming contracts or requests for proposals for this category of system are anticipated in the near, or not too distant future, in Australia, Canada, Croatia, Greece, Kuwait, New Zealand, Saudi Arabia, Turkey, U.A.E., UK, USA.

The leading manufacturers in the Medium Range and Medium Range Endurance categories are: AAI Corp/USA, GEC-Marconi/UK, General Atomics/USA, IAI/Israel, Kentron/South Africa, Meteor/Italy, Oerlikon-Contraves/Switzerland, Pioneer Inc/USA, Sagem/France, Silver Arrow/Israel, STN Atlas Elektronik/Germany.

MALE & HALE UAVs - Corps Level

The second, but much smaller wave, that is now starting to form concerns the high value tactical MALE (medium altitudfe long endurance) and strategic HALE (high altitude long endurance) UAVs; such systems have been developed by IAI/Israel, Silver Arrow/Israel, General Atomics/USA, Lockheed & Boeing/USA, Teledyne Ryan/USA. Only the USA military establishment has actually funded the development of this type of UAV systems (Darkstar, Global Hawk, Predator). Firm interest in these types of systems is, for the moment, principally restricted to the richer and more developed countries (Australia, France, Germany, Israel, Italy, Japan, Netherlands, Spain, Sweden, Turkey, UK, USA), but it should be noted that China, Iran, ROC-Taiwan are

Client Country	System in Service	Manufacturer (Prime Contractor)	On Order Or Programmed
Australia	Nulka	BAe Australia, Australia Teledyne Aeron., USA	Global Hawk ?
Austria		Ongoing RFP	Tactical UAV
Algeria		Kentron, South Africa	Seeker
Bahrain		BAI Aerosystems,USA	Dragon
Belgium	Epervier → ♦	MBLE Déf., Belgium IAI, Israel + Eagle, Belg.	Hunter B
Bulgaria		Techno-Sud,France	Vigilant
Canada		RFP delayed	Tactical UAV
Chili		Ongoing competition	Tactical UAV
Czech Rep.	Sojka III	VTUT à PVO,Czech Rep.	
Denmark		Sagem, France	Sperwer
Egypt	Scarab ♦ SkyEye ♦	Teledyne Ryan, USA Lear Astronics, USA Ongoing competition Ongoing rqmt (FMS)	Tactical EW UAV VTOL UAV
Finland		Oerlikon-Contraves, CH	Ranger
France	CL289 ⇓ Crecerelle Vigilant ♣ Hunter ♣	Aérospatiale/Dornier Cac Systèmes, France Sagem, France Techno-Sud, France TRW/USA & IAI/Israel	Sensor upgrade Fox MLCS Heliot EW Crecerelle
Germany	KZO (Brevel) LUNA CL289 ⇓	Eurodrone (STN Atlas) STN Atlas, Germany EMT, Germany Dornier/Aérospatiale	(KZD) Brevel Taifun & Mücke LUNA Sensor upgrade
Greece		Upcoming RFP	Tactical UAV
India	Searcher	ADE & Taneja Aerosp. Bangalore, India IAI, Israel	Nishant Searcher
Israel	Scout & Harpy Searcher Hermes 450S	IAI-Malat, Israel IAI-Malat, Israel Silver Arrow, Israel	
Italy	Mirach 20 & 26 Mirach 100	Meteor, Italy Meteor, Italy General Atomics	Mirach 150 Predator
Morroco	SkyEye ♦	Lear Astronics, USA	
Netherlands		Sagem, France EMT, Germany	Sperwer LUNA
Romania	Shadow 600 Vigilant	AAI Corp., USA Techno-Sud, France	Shadow 600 ?
Russia	Shmel-1	Yakovlev, Russia	
Singapore	Scout ⇓ Searcher II	IAI, Israel Upcoming competition	Searcher II Tactical UAV
South Africa	Seeker	Kentron, South Africa ATE, South Africa	Vulture
South Korea	Searcher Harpy	AAI Corp, USA Daewoo, South Korea IAI, Israel IAI, Israel	Shadow 400 Bijo
Sri Lanka	Scout ♦ ⇓	IAI, Israel | Ongoing RFP	Tactical UAV
Sweden	RPG MK III ♣ Ugglan	Techmont, Sweden Sagem, France Mission Techno., USA	Mini-Vanguard ♣
Switzerland	Ranger	Oerlikon, Switzerland	Ranger
Thailand	SkyEye ♦ Searcher II ♣	Lear Astronics, USA IAI, Israel	
Turkey	GNAT 750	General Atomics, USA Ongoing competition	Tact & Strat. UAV
U.A.E.	Seeker	Kentron, South Africa Upcoming RFP	Tactical UAV
UK	Phoenix	GEC Marconi Avionics 2 Upcoming RFPs	Sender& Spectator
USA	Camcopter ♣ Exdrone/Dragon Global Hawk Hunter ♣ I.GNAT Outrider ♣ Pioneer Pointer Predator Sentry	Schiebel, Austria BAI Aerosystems Teledyne Aeronautical TRW, US & IAI, Israel General Atomics Alliant Techsystems Pioneer UAV Inc. AeroVironment General Atomics S-Tec Ongoing competition Ongoing competition	Camcopter Global Hawk Predator Tactical UAV VTOL naval UAV

Figure VII - UAV Systems : Deployed, On Order or Programmed

Explanation : → = end of service life ⇓ = nolonger in prod.
♦ = nolonger fully operational ♣ = test/eval. system

Figure VIII **Review of the Currently Existing MALE & HALE UAVs**

Characteristics	HERON (Eagle) MALE	HERMES 1500 MALE	I.GNAT MALE	PREDATOR MALE	GLOBAL HAWK HALE	DARKSTAR HALE (cancelled)
Altitude :						
Max m	9150	9145	> 7620	7925	19800	15200
Operating m	8075	8000	7620	4600	15-19200	15200
Endurance						
Max. hours	50	> 40	40	> 40	38	12
Action radius km	926	200 km	700	926	5556	>926
Speed						
Max. km/h	....	315	230	210	>639	556
Cruise km/h	231	241	140	125	639	556
Loiter km/h	130 - 148	148	120	115	630	241
Climb rate						
Max. m/min	198	457	?	244	1036	610
Deployment	?	?	Multi C-130 sorties GS: Multi C-141,	Multi C-130 sorties or C-5 sorties	AV: Self-deployable	Multi C-141, C-17
Propulsion	1 x 4 cyl., 4-stroke pusher propeller	2 x 4 cyl., 4-stroke 2 x pusher prop.	1 x 4 cyl., 4-stroke pusher propeller	1 x 4-stroke pusher propeller	1 x turbofan	1 x turbofan
- Producer	Rotax	Rotax	Rotax	Rotax	Allison	Williams
- Model	914	914	912 or 914	912 or 914	AE3007H	FJ44-1A
- Rating	75.8 kw - 105 HP	75.8 kw - 105 HP	63.4 kw - 85 HP; or 75.8 kw - 105 HP	63.4 kw - 85 HP; or 75.8 kw - 105 HP	32 kN	8.45 kN
- Fuel type	AVGAS (100 oct.)	AVGAS (100 oct.)	AVGAS (100 oct.)	AVGAS (100 oct.)	Heavy fuel (JP-8)	Heavy fuel (JP-8)
- Cap. liters	720	?	309	409	8176	1575
Weight :						
Empty kg	600	?	385	544	4055	1978
Fuel kg		?	227	300	6668	1470
Payload kg		400	91	204	889	454
Fuel + payl. kg	500					
Max. TO kg	1100	1500	703	1134	11612	3901
Dimensions :						
Wingspan m	16.60	10.00	12.80	14.80	35.40	21.00
Length m	8.50	8.60	5.75	8.10	13.50	4.60
Height m	2.30	?		2.20	4.60	1.50
Avionics :						
Transponder	Mode IIIC IFF ?	Mode IIIC IFF ?	Mode IIIC IFF	Mode IIIC IFF	Mode I/II/IIIC/IV IFF	Mode IIIC IFF
Navigation	GPS & INS	GPS & INS	GPS (INS option)	GPS & INS	GPS & INS	GPS & INS
Launch/Recovery	Runway	Runway	Runway	Runway (760 m)	Runway (1524 m)	Runway (<1219 m)
Comm. & Control	Remote control & preprogrammed	Remote control & preprogrammed	Remote control & preprogrammed	R.Contr/Prepgmd/ autonomous	Preprogrammed/ autonomous	Preprogrammed/ autonomous
Sensors	EO/IR, maritime radar (Elta)	EO/IR	EO/IR, SAR	EO, IR, SAR	EO, IR, SAR	EO or SAR
Data links :						
Type Uplink	C-band LOS	C-band LOS ?	C-band LOS	G-band LOS (Ku-band growth)	UHF LOS & Satcom X-band	UHF LOS & Satcom X-band
Downlink	C-band LOS	C-band LOS ?		Ku-band Satcom J-band Satcom	CDL LOS & Ku-band Satcom	CDL LOS & Ku-band Satcom
Bandwidth	20 MHz	?	20 MHz ?	C-band : 20 MHz Ku-band Satcom : RL/CL 5/9 MHz	UHF LOS/Satcom : 25/25 kHz X-CDL LOS: RL/CL: 137/64 MHz Ku-Satcom: RL/CL: 3-69/0.26 MHz	UHF LOS/Satcom : 9.6/25 kHz DAMA X-CDL LOS: RL/CL: 137/64 MHz Ku-Satcom: RL/CL: 26/(N/A)MHz
Data rate : - analog Hz - digital bps	20 MHz	?	20 MHz ?	C-band : 20 MHz Ku-band : RL : 1.544 Mbps CL : 64 kbps	UHF : 9.6/9.6 kbps X-CDL : RL : 137 Mbps CL : 200 kbps Ku-Satcom : RL : 1.5-48 Mbps CL : 200 kbps	UHF : 4.8/1.2 & 2.4 X-CDL : RL : 137 Mbps CL : 200 kbps Ku-Satcom : RL : 1.54 Mbps CL : (N/A)
C2 Links	Through data link	?	Through data links	Through data links	Through data links	Through UHF LOS, UHF Satcom, or CDL LOS
Prime or Key Contractors	Israel Aircraft Ind. (& Matra BAe Dyn.)	Silver Arrow	General Atomics	General Atomics Aeronautical Syst.	Teledyne Ryan Aero	- Lockheed Martin - Boeing

also starting to express interest in this type of UAVs.

The first prototype of Teledyne Ryan's Global Hawk HALE UAV was rolled out in February 1997. Its first flight took place in February 1998. The second prototype flew for the first time in November 1998; it was lost in crash in March 1999. This unfortunate accident has apparently not hampered the USAF's ardour, nor brought the programme's financing into danger. Global Hawk is the only UAV in its category currently flying, and it is doubtful if a similar aircraft will be rolled out in the near future by another manufacturer. Nevertheless, it should be mentioned that several development studies for HALE UAVs are currently ongoing (Aerospatiale/France, Dassault Aviation/France, Saab/Sweden).

General Atomics Aeronautical System's Predator MALE UAV is an improved and larger version of the initial GNAT, and an eviable success story. General Atomics was initially awarded a US$ 31,7 million, 30 month Advanced Concept Technology Demonstration contract (10 A/Cs & 3 GCSs) by the US Navy in January 1994. Since then, over 55 aerial vehicles have been ordered by the USAF and CIRPAS (35 A/C delivered), and Predators have been extensively deployed over Bosnia, and more recently over Kosovo, logging in total more than 13.000 flight hours.

The Italian Ministry of Defence is has programmed the purchase of a Predator system (6 aircraft, 1 or 2 GCSs) for the beginning of 2000. The Italian Air Force will operate this system. The possible second ground control station would be used onboard an Italian Navy ship. One of the system's initial pressing tasks will be the surveillance of the Adriatic Sea for clandestine immigrant and smuggling control.

The United Kingdom MoD is looking at the possibility of leasing a Predator system for approximately one year in order to gain operational experience within a short

timeframe, prior to formulating operational requirements.

France is currently in the process of evaluating several MALE contenders (Eagle Star-Matra BAe Dynamics & IAI/Israel, Predator-Sagem/France & General Atomics/ USA). In this context, it is of interest to mention that the French MoD-DGA has decided to use a highly sophisticated software simulation tool developed by Dassault in cooperation with ONERA (French aeronautical research organization), to compare the system software of the various proposed UAV systems. Aérospatiale Matra and Dassault Aviation are both active within in-house development work in the field of HALE UAVs.

Germany has initiated a study contract relative to MALE UAVs, and is rumoured to be reconsidering the Grob airframe as the basis of an indigenous MALE UAV.

Turkey, whose military froces already operate the GNAT UAV system (General Atomics Aeronautical, USA), issued an extremely ambitious request for proposal in 1998 concerning three different types of UAVs, with a reported budget of approximately US $ 500 million budget. The Turkish Ministry of Defence received proposals from Catic/China, General Atomics/USA, and IAI/ Israel. This requirement has been downscaled (only two types of UAV systems now constitute the requirement) and the financial implications of the recent earthquakes have further sapped the Ministry of Defence's budget, and this has caused an even further decrease of the requirement.

The Australian Ministry of Defence (Royal Australian Air Force) has expressed very keen interest in the Global Hawk. One of the principal purposes Australia would like to put this system to, is the control of the waters to the north east of the continent for illegal immigrant and regional surveillance. The interest is so keen that under an A$ 30 million agreement announced ni March 1999, Australia's Defence Science and Technology Organization is to cooperate with the USAF and Teledyne to develop a maritime surveillance version of Global Hawk's current synthetic aperture radar and evaluate the system's suitability to meet the RAAF's requirement.

An overview of the current MALE and HALE UAVs can be found in Figure VIII. For reference purposes, this table also includes the now cancelled DarkStar HALE. The DarkStar HALE system was developed under a 31 month ACTD contract awarded by ARPA to Lockheed Martin and Boeing in June 1994. The first prototype was rolled out in June 1995 and flew for the first time in March 1996, and subsequently crashed in April 1996. The second prototype flew several times, before the programme was terminated by the USAF, reportedly after having come to the decision that its military utility was insufficient to justify completion. However, the idea should not be excluded that the DarkStar development will continue as a "black" programme.

TACTICAL UAVS - Regimental/Brigade Level

A third and potentially larger UAV wave, which is currently starting to form, concerns brigade/regimental level fixed and rotary wing tactical UAV systems. The applications of these systems include: over-the-hill reconnaissance, aerial mine detection, urban warfare, NBC monitoring, communications relay. Interest for this category of systems has been expressed by Australia, Austria, Bahrain, Croatia, France, Germany, Singapore, Sweden, UK, USA). The applications of these systems include: over-the-hill reconnaissance, aerial mine detection, urban warfare, NBC monitoring, communications relay.

The leading manufactuers in this category are: AeroVironment/USA, BAI Aerosystems/USA, CAC Systèmes/France, EMT/Germany, Mission Technologies/USA, Scandicraft/Sweden, Schiebel Elektronische Geräte/Austria, Sikorsky Aircraft/USA, Silver Arrow/Israel, S-TEC/USA, Silver Arrow/Israel, STN Atlas Elektronik/Germany, Techment/Sweden, and Techno-Sud Industries/France.

These systems will probably be the most accessible, the easiest to exploit and the simplest to integrate into the military structures of non-industrustrialized and lesser sophisticated countries. In this category of UAV systems, Sweden has actively explored the potential of a rotary wing aircraft, namely the RPG III, a gyroplane-based UAV with vertical take-off and very short landing characterics.

The Swedish Coastal Artillery is rumoured to have awarded a sole source contract to Mi-Tex, USA for the supply of a single Mini-Vanguard UAV system for experimental purposes; this UAV incorporates Ti-Tex's well-known twin-wing principal, that was also used on Alliant TechSystems' Outrider UAV. Delivery is said to be scheduled for December 1999.

The Royal Netherlands Army has recently purchased a Luna UAV system from EMT, Germany for experimental purposes.

The Bahrain Defence Forces have just taken delivery of Dragon UAVs from BAI Aerosystems, USA.

Requests for Proposal and contracts for such systems may be expected in Germany (AAMIS programme), the Netherlands (Luna, as an extension of the joint German-Dutch Fennec programme; Luna is part of the German Fennec reconnaissance system), Sri Lanka (to replace the IAI Scouts, that have now all crashed), UK (Sender programme).

These relative small and highly mobile UAV systems are rather price-sensitive, but also seem to offer, in time, the largest production volume and sales potential. The sales of these systems will probably face less obstacles than larger tactical UAV systems to find new customers, as they will be substantially cheaper, easier to deploy and operate, incorporate less sensitive and more commercial-of-the-shelf components.

VTOL UAVs

While most of the aforementioned UAVs concern fixed wing aircraft, it is to be noted that distinct interest is starting to be shown in UAVs for urban reconnaissance surveillance, EW and psy ops roles during conditions of civilian unrest, strife and war, littoral warfare, land and sea mine detection, naval communication relay, naval over-the-horizon targeting and landing naval supplies, and that the aircraft being considered for these roles all seem to be either VTOL or S/TOL UAVs.

Operational scenarios for VTOL UAVs have already been indentified in a number of countries (e.g. Egypt, France, Germany, Japan, Sweden, USA) and have resulted in the definition of operational requirements.

A number of other countries, including Saudi Arabia and South Africa, are in the process of formulating operational requirements. Recently, Egypt issued a RFP for VTOL UAVs (which were specified as having to be of American origin as they were to be purchased with FMS credits). The US Marine Corps has just awarded a development contract to Sikorsky for the development of the Cypher II, a winged version of the circular shrouded

rotor UAV, which has a pair of four-blade, coaxial, bearingless rotors. This new UAV is to be called Dragon Warrior and is aimed at an urban warfare role.

Figure IX VTOL Categories	Payload Cap. in kg	Mission Radius in km	Endurance in hours
1- Land-launched	10-25	in-sight	1-2
2- Land- & Ship-Launched	30	25-30	3 at 25-30 km
3- Land-launched	50	50	1-3
4- Ship-launched	50	100	2 at 100 km
5- Land- & Ship-Launched	>50	>100	5 & more

Taking into account payload capacity, operational range and flight endurance, VTOL UAVs can be categorized as indicated in Figure IX.

The principal problem in the development of VTOL UAVs is to make them fully autonomous, including out-of-sight precision hovering and automatic take-off & landing, including from & on naval ships. The 1998 US Navy VTOL demonstration has shown the current level of technology maturity in these areas.

As things stand at the moment in relation to ATM issues, VTOL UAVs may have an easier entry into a commercial UAV market (captive & potential) than fixed wing UAVs, which probably explains the fact that considerable R&D efforts are being deployed in this field all over the world. Japan is the forerunner; today more than 2000 VTOL UAVs are being commercially operated there by specialized and certified operators.

OFFENSIVE UAVs

Lethal UAVs can be considered as a cost-effective version of a cruise missile. Strictly speaking, they do not, in their operational configuration, fit the definition of UAVs given earlier, as they are expendable and not reusable. However, they can also be seen as an extrapollation of UAVs, using detection & identification sensors and mission software specific to their mission.

Seen from a volume, some of the largest UAV contracts recently concluded, concerned offensive UAVs (STN Altas Elektronik's anti-vehicle & anti-structure "Taifun" in Germany & IAI's anti-radar "Harpy" in South Korea).

The fully programmable and autonomous Taifun is intended to attack selected tanks, artillery, radar posts, command structures and logistical assets well behind enemy lines. Taifun will be equipped with a high-resolution K-band millimeter wave radar (MMW) seeker with a moving target indication (MTI) and Doppler beam capability, and a shaped charge warhead. It is to be launched in swarms from truck-mounted launching canisters and then continues on its preprogrammed flight mission to the search zone where it can loiter at 120 km/h for 4 hours searching for its preprogrammed targets. Once the required target has been detected, recognized and identified, Taifun can either operate as a fire-and-forget weapon, or be directed by operator in its final kill phase. Full-scale development of the Taifun was launched in late 1997 and the first system is programmed to be delivered for operational and qualification tests in 2003.

The programmable anti-radiation Harpy offensive UAV is based on the DAR, originally developed by Dornier,Germany, and is equipped with a high-explosive warhead. It is launched by means of a booster rocket from a truck-mounted container. It has been reported that during NATO's recent offensive against Serbia, serious consideration was given by the US to the deployment of Harpy offensive UAVs.

Cutlass is a variant of Harpy, developed by IAI in cooperation with Raytheon E-Systems, USA for the suprression of enemy air defence (SEAD) role; Cutlass uses the seeker head of the AIM-9 Sidewinder anti-aircraft missile (Raytheon) and the automatic target recognition and classification algorithms also developed by Raytheon.

CAC Systèmes, France is developing the K100 anti-structure and vehicle lethal UAV, which is said to be equipped with a video homing device and compatible with several existing warheads, including that of the Matra Apilas anti-tank missile.

Kentron, South Africa, under contract to the South African Air Force, has developed the autonomous anti-radiation Lark for SEAD and an anti-radar roles; however, due to governmental financial restrictions the Lark has not entered into service.

Sagem has perfected the anti-radiation Marula, which it acquired through their take-over of Aéronautiques & Systèmes, France (AES). It is of interest to remark that the origin of the Marula can also be found in South Africa, where initial development had taken place prior to the project being purchased by AES. Both developments were auto-financed by the involved companies.

ARMED UAVs

The feasibility of equipping UAVs with laser designators has already been proven. There are now also ongoing studies in the USA related to the fitting of larger UAVs with existing missiles (e.g. Hellfire) to conduct missions such as SEAD, urban warfare, precision strikes against targets of opportunity discovered during surveillance missions and the support of special forces.

The boost phase intercept of ballistic missiles using anti-missile missiles launched from a high circling UAV is also seriously being considered (Israel, USA).

Initially, Armed UAVs will be fitted with existing, and possibly slightly modified, weapons and/or weapon delivery systems. As the concept is refined, and their operational advantages are proven, it stands to reason that specific weapon systems will be developed for these aircraft.The UAVs that can be considered for such a role are very much in function of the payload capacity required to carry the relative weapon system and the fuel necessary to bring the UAV to the theatre of operations. It can be envisaged that Armed UAVs could be land-, ship- and air-launched. It can also be envisaged that droned (formerly piloted) aircraft could be used for this role.

It stands to reason, that Armed UAVs will be a necessary stepping stone towards the future uninhabited combat aircraft (UCAV).

LIGHTER-THAN-AIR UAVs

It is of interest to note that lighter-than-air UAVs, in other words droned airships, are starting to be spoken about. In fact, these systems offer substantial advantages for a certain number of missions where speed and vulnerability are not of extreme importance. The scenarios that could be envisaged are not necessarily military. Extremely dull missions, and which can be totally automated, such as advertising, forest fire control, forestry inspection, crop inspection, power line inspection, cargo transport, searching for tuna concentrations, meteorological purposes, ice & snow cap measurement, communication relay platform, mapping, filming certain sports events (offshore powerboat & sailing races), as well as a number of environmental research applications.

Currently, lighter-than-air UAVs are being used by broadcast TV teams for sportscasting and filming rock concerts (principally indoors).

Other missions that these craft could be used for include fishery control, economic interest zone monitoring, smuggling control, ship traffic monitoring.

Companies involved with the development of this type of UAV include :

- Advanced Hybrid Aircraft Inc., USA
- Aviation Industries of China, China
- Envol Images, France
- Pan Atlantic Aerospace, Canada
- Promotional Ideas Group, UK
- Shanghai Aircraft Research Inst., China
- Skypia Company Ltd, Japan
- Skysat Systems Corp., Canada
- University of Stuttgart, Germany

MICRO UAVs

The distant buzz of Micro UAVs is starting to be picked up. Interest in these systems has been recognized in France, Germany, Greece, Italy, Israel, Sweden, UK and USA, but to field this type of UAV substantial technological hurdles still have to be overcome.

The basic idea behind Micro UAVs is to increase situational awareness down to platoon level. They are envisaged to carry out missions in two types of environment: - urban areas;
- open terrain.

In urban areas Micro UAVs will fulfill day and night reconnaissance and surveillance roles, which will possibly also include the requirement to inspect the inside of buildings from the outside, or flying into them. This will require relatively slow flying and highly manoeuvrable aerial vehicles with low acoustic signatures, which will have to be equipped with some form of obstacle detection and collision avoidance system.Line-of-sight communications in this application will be pratically impossible, hence a new approaches must be investigated.
In open terrain Micro UAVs are expected to not only fulfill stand-off day and night reconnaissance and surveillance roles, but also roles such as unattended static surface sensor (e.g. EO, IR, acoustic, vibration), bacterological and chemical agent detection, communications relay, radar and communications jammer.

From the aforementioned it can be concluded that military operations in urban terrain (MOUT) will favour some form of VTOL UAV, and that military operations in open terrain will favour fixed wing UAVs. In both cases Micro UAVs will have to incorporate a high degree on onboard intelligence, be easily carriable and deployable by a soldier by means of a compact and robust ground control station and launch system.

The classic laws of aerodynamics and aircraft design to not apply to Micros, as their small size and low weight make them more akin to flying insects and birds than aircraft. In some cases, the approach being taken by designers is resulting in aerial vehicles, which ressemble flying insects, bats or birds and use trailing antennae as stabilizers.

Entomopters (electromechanical insects) and ornithopters (electromechanical birds) are being researched as possible solutions. Georgia Tech Research Institute is developing, in collaboration with the University of Cambridge, UK and ETS Labs, an entomopter using a propulsion unit based on a reciprocating chemical muscle, which converts chemical energy into motion by means of a non-combustive chemical reaction.The California Insitute of Technology is developing, in collaboration with AeroVironment, an ornithopter designated Microbat, which creates flight movement by flapping its wings, which are propulsed by a micro-electro-mechanical system.

In all cases innovation is required in many fields, such as micro power supply, micro propulsion, micro imaging sensors, micro altimeters, low power micro datalinks, low power micro electronics, and low power micro GPS. One can envision the downlinked imagery being displayed not only on the miniature screen of an individual soldier's handheld control station station, but alternatively also on the head-up display integrated into his helmet.

At this point in time, only the US DoD is making sizeable amounts of money available for research & development and studies relating to the future warfighter's individual UAV. The US Defence Advanced Research Projects Agency (DARPA), and the US Naval Research Laboratory (NRL) with funding from the US Office of Naval Research, have both initiated micro aerial vehicle programmes. DARPA's programme is a US $ 35 million, 4-year effort, that began in 1997 with the award of nine innovative research contracts (US $ 100.00 each) for the development of operating concepts and to demonstrate flight-enabling technologies. In 1998 four of the contracts progessed into Phase 2:

- Sanders, teamed with Lockheed Martin Skunk Works and General Electric Corporate R&D center) received the first US $ 690.000 of a US $ 10 million, 42 month contract for the development of the fixed-wing MicroStar micro. This μUAV is expected to weigh 85 gram and have a 15 gram EO payload and is controlled, by means of way points, by means of a laptop computer, a PCMCIA card and a 1 m wide folding umbrella dish.
- Lutronix Corp. received a US $ 200.000 study contract for its 4 inch rotary wing micro UAV, which is destined for urban reconnaissance.
- AeroVironment received a US $ 750.000 contract to develop micro UAV concepts for use in relatively open terrain, urban areas and jungle. AeroVironment has focussed on a non-hovering disc aircraft with a diameter of 15,24 cm weighing 50 gram distributed as follows :

Lithium battery	26 gram
Engine	7 g
Gearbox	1 g
Propeller	2 g
Airframe	4 g
Control actuators	1 g
Receiver & CPU	1 g
Downlink TX	3 g
B/W video camera	2 g
Interface electronics	1 g
Roll rate gyro	1 g
Magnetic compass	1 g

- Aerodyne Corp. received a US $ 750.000 contract to develop the Hyperav hovering disc micro UAV; it is expected to weigh up to 300 gram and will probably be powered by liquid fuel.

In all cases the aerial vehicles can be either hand-, munitions- or platform-launched, must be capable of transmitting near-real-time imagery, but must not exceed 15,24 cm (6 inches) in any dimension, be able to fly up to six miles at 64 to 80 km/h (40 to 50 m/h) and have an endurance of 20 min to 2 hours.

The following manufacturers also had technology demonstrations carried over into Phase 2 :

- M-Dot Inc. received a US $ 750.000 contract to continue development of a 1.4 lbf.-thrust gas turbine (dim. : length 7,62 cm, ø 4,318 cm), which was intended to be used on the Hyperav (Aerodyne, USA).
- IGR Enterprises Inc. received a US $ 750.000 contract to demonstrate a solid oxide fuel cell for micro UAVs, which is to supply enough energy to fly a 50 g micro UAV for several hours, while powering its payload. This fuel cell is to be flown on AeroVironment's micro.

Figure X	US Micro UAV Design Parameters	
Airframe types	- Rotary Wing - Fixed wing - Hovering disc - Insect wing - Ornithopter	
Contracting Authority	DARPA	Naval Research Lab
Size (max)	6 x 6 x 6 inches	wingspan: 6 - 8 inches
Weight (empty)		50 - 100 gr
Payload cap.	not defined	15 gr
Missions	RSTA, BDA, coms relay, NBC sensing	Sensor emplacement
Payload	- EO (B/W -> colour) - microphones - NBC sniffer	Radar jammer
Image Tx	near-real-time	not applicable
Type of engine	- gas turbine - electric - electrostrictive polymer muscles - piezoelectric actuators - silicon turbojet - kerosene internal combustion engine	electric
Launch methods	- hand-launch - munitions launch - platform-launch	- hand-launch - from larger UAV
Range	9,66 km	3 - 5 km
Endurance	20 min - 2 hours	20 minutes
Speed	64 - 80 km/h	32 - 64 km/h

- SRI International and the University of Toronto received a US $ 590.000 contract (which could grow to US $ 2 million over 36 months) for the development of a +/- 15,24 cm ornithopter µUAV powered by electrostrictive polymer articial muscles.
- Vanderbilt University received a contract to mimic insect flight using piezoelectric actuators to resonate a thin metallic structure that actuates the wings. The contract could be worth US $ 738.000 if options are excercised.
- California Institute of Technology (teamed with AeroVironment and the University of California-Los Angeles) received a US $ 1,8 million contract (if options are excercised) to study and possibly fly a 10 gram flapping "Microbat", which will carry microphone arrays for acoustic homing in on sounds.
- Massachusetts Institute of Technology received a contract that could be worth US $ 2 million to develop a shirt button-sized hyrogen-fueled silicon micro turbojet weighing 1 gram, producing 13 grams of thrust to propel a 50 gram µUAV.
- D-Star Engineering received a contract with a value of US $ 650.000 (if options are excercised) to make a kerosene internal combustion engine, which could possibly be a muffled ceramic diesel engine weighing 20 g, measuring 2 cm and producing 80 watt shaft power.
- Technology in Blacksburg Inc. received a contract with an initial value of US $ 150.000 (US $ 950.000 with options) to explore thermoelectric generators to recover waste heat from inefficient small engines.

The NLR has specified that their µUAVs can have a wingspan of 15,24 to 20,32 cm (6-8 inches); they are expected to weigh 50 to 100 gram, carry a 15 gram payload and fly for up to 20 minutes at 32 to 64 km/h using an electric engine. Fuel cells under development at DARPA will provide higher energy density and power levels than the lithium batteries currently available. The US Navy envisions launching their micro UAVs either by hand or from a larger UAV, which will then fly autonomously with a radar jamming payload (still under development) and land unnoticed on the radar dish. The first flight demonstrations are planned in 2001. The NRL's Tactical Electronic Warfare Division is responsible for the design of the aerial vehicle and systems integration. It has designed a twin engine Micro Tactical Expendable UAV to meet DARPA's design parameters.

The US Office of Naval Research is also sponsoring, in collaboration with DARPA, an investigation into insect aerodynamics by the University of California. The goal of this five-year programme is to develop a robotic fly with a diameter of 5 to 10 mm, that can transit over a short distance and maintain a stable hover.

The following US companies currently have Micro UAV development programmes underway:

	Designation	***Type of Airframe***
AeroVironment	BlackWidow	Non-hovering disk
AeroVironment, UCLA & CIT	Microbat	Flapping wing
Aerodyne	Hyperav	Hovering disk
D-Star	D'Spyfly	Flying wing
Georgia Tech	Entomopter	Flapping wing
Lutronix	Kolibri	Rotary wing
MLB	- Bat	Flying wing
	- Micro Dot	Non-hovering disk
	- Trochoid	Flying wing
Sander, Lockheed Martin & GE	- MicroStar	Fixed wing
	- MiniStar	Fixed wing
SRI Internat. & Univ. of Toronto	Mentor	Flapping wing
Vanderbilt University	?	Winged crawling insect

AeroVironment has reported flights of up to 20 minutes with its Black Widow.

As can be seen from the aforementioned, there is considerable acitivity in the US in this field, and universities are heavily involved. The funding is principally being put up by DARPA and the Office of Naval Research.

In Europe there is as yet no government funded micro UAV-related research and development programme with a clear objective.

However, the French Ministry of Defence (DGA) is planning to shortly initiate and fund (possibly jointly with other European MoDs) an European-wide competition relative to the development of micro UAVs. Teams composed of universities, industry and R&D institutes will be given a detailed scenario for which micro UAVs are to be developed. It is to be hoped that this will chrystalize R&D in this field in Europe, as the commercial and financial implications of the technological spin-offs could be extremely rewarding, aa the emerging technologies could have multiple other military and non-military applications.

LOW ALTITUDE LONG ENDURANCE UAVs

This is a relatively small category of UAVs. However, due to the exceptional performance of these aircraft, they are considered to warrant a separate classification. Currently, the operational systems that belong to this category are:

- Aerosonde	Aerosonde Robotic Aircraft	Australia
- Laima	Insitu Group	USA
- Pelican	US Navy Center for Interdisciplinary Remotely Piloted Aircraft (CIRPAS), USA	

All three of these aircraft are used for meteorology measurements.

Aerosonde has been developed by Aerosonde Robotic Aircraft (formerly known as EES), Australia in cooperation with the US Naval Research Laboratory. This 15 kg UAV is used for over-ocean meteorological sensing purposes in Australia by the Australian Bureau of Meteorology and in Taiwan by that country's Central Weather Bureau, and has also flown such missions much out Japan. It's extremely long endurance of 32 hours is made possible by a specially modified single-cylinder four-stroke engine, driving a two-blade fixed- pitch pusher propeller. The consumption of this aircraft is exceptionally low. As illustration, it should be mentioned that this aircraft

can stay aloft for 32 hours with only seven litres of low lead Avgas 100.

Laima is the American cousin of the Australian Aerosonde, produced by Insitu Group. This UAV has been operated on behalf of the World Health Organization, the US Office of Naval Research, the US National Oceanic and Atmospheric Administration, US de^partment of Energy and the US National Weather Serice. In 1998 Laima was the first UAV to cross the Atlantic from Canada to the United Kingdom (Hebrides). Both Laima and Aerosonde could quite possibly change the way weather is currently forecast, and play a very important role in improving hurricane and storm prediction..

Pelican is a modified Cessna 337 Skymaster (deletion of nose-mounted engine & replacement of rear engine by a more powerful one) that was developed by the US Office of Naval Research for low-altitude long endurance atmospheric and oceanographic sampling, with the support of NASA's Environmental Research Aircraft and Sensor Technology (ERAST) programme. General Atomics Aeronautical, USA, under contract to CIRPAS integrated the Predator flight control package into the aircraft. The aircraft is flown by means of CIRPAS's Predator ground control station.

OPTIONALLY PILOTED AIRCRAFT

Optionally or alternatively piloted UAVs (OP.UAV) are existing certified manned aircraft, which have been fitted with the necessary control system, thereby turning them into aircraft that can be operated without a pilot. Such aircraft can be fixed or rotary wing aircraft. The following OP.UAV examples can be mentioned:

CM-44	fixed wing	California Microwave, USA
Heliot	rotary wing	CAC Systèmes & EDT, France & Dragonfly , Italy
K-Max	rotary wing	Kaman, USA
Pelican	fixed wing	CIRPAS, USA
Vigilante	rotary wing	SAIC, USA

There are also several studies underway in this area in Europe concerning the droning of ultralights and high-flying research aircraft. Optionally piloted aircraft have a number of advantages:

- the airframe is relatively inexpensive;
- the payload capacity is relatively high;
- because they are certified, they can be flown in the same airspace as a piloted aircraft, as long as a pilot is onboard and the aircraft can comply with all existing rules and regulations (See & Avoid);
- they can be used as a testbed to evaluate and validate various types of UAV payloads;
- and possibly even more important, they can be used to used to prove datalink and command & control link reliability for airworthiness certification purposes, which should help build user confidence and acceptance, which is essential, if the UAV market is to expand.

It is mentionworthy, that CAC Systèmes, France has been awarded a contract by the French INTRA Group for a Heliot UAV system. This optionally piloted rotary wing aircraft is to be used as a surveillance and command & control relay UAV by INTRA, a French organization responsible to monitor nuclear facilities in the case of an accident. To accomplish this INTRA uses a number of different unmanned ground vehicles (UGVs) for various intervention and surveillance purposes; these UGVs will now be controlled via Heliot.

The Vigilante VTOL UAV under development by SAIC, USA, and one of the contenders for the US naval VTOL UAV requirement, is also based on a manned helicopter.

The K-Max (Kaman, USA) will be evaluated by the US Marine Corps as an autonomous UAV for delivering externally slung loads during resupply missions.

OP.UAVs could quite possibly become in important instrument in the critical airworthiness certification process, and will most probably play a required intermediate role in the UCAV development process.

UCAVs

The far rumblings of uninhabited combat aerial vehicles (UCAVs) are now also starting to be heard. This is still a rather obscure area, due to the classified nature of these development programmes, but a number of UCAV-related studies, evaluations and demonstrations are taking place. Basically, two types of UCAVs being considered :
a) aircraft-based designs;
b) (cruise) missile-based designs.

The driving forces behind the interest in UCAVs can be distilled down to the following :

- they are less expensive than manned aircraft (less maintenance, no pilot & no pilot-related safety);
- they are less expensive than expendable cruise missiles (they are reusable);
- they are capable of very high manoeuvrability & speed (much more than a pilot could support).

The roles for which UCAVs are most cited are the suppression of enemy air defences (SEAD) and deep strike missions in heavily defended sectors. In such roles UCAVs are to be seen as support systems for manned aircraft and not replacements. They are envisioned to be operated either from a ground or an airborne control station, manned combat aircraft, or a combination of these. UCAVs will require to be able to transmit large volumes of real-time and secure data to their operators; they will be required to be fitted with multiple and powerful imaging systems linked to automatic high speed target identification systems.

In 1997, the UK MoD launched a US $ 57 million study of options relative to the Future Offensive Air System (FOAS), which is scheduled to replace the Tornado fighter, beginning in 2015. UCAVs are one of the options considered. The MoD has awarded a number of study contracts for the definition of UCAVs.

In 1997 Lockheed Martin and Tracor Inc. (now BAe, UK) announced their collaboration to drone a F-16 fighter (OP.UAV?) and use this aircraft as a UCAV surrogate for further technology development.

In 1997 the US Navy selected Lockheed Martin to develop a concept for a submarine-launched VTOL UCAV to be launched from ballistic missile tubes. This is one of the UCAV concepts being pursued by the Naval Air Systems Command.

In 1998 the French MoD-DGA and the US Air Force formed a teaming arrangement to develop flight control and flight management technologies that are to allow the interoperability of manned aircraft and UCAVs for strike missions.

In 1998 DARPA and the US Air Force awarded a US $ 4 million 10-month study contract to four contractors (Lockheed Martin Tactical Aircraft Systems, Northrop Grumman, Raytheon, and Boeing Phantom Works) as part of an Advanced Technology Demonstration Pro-

gramme to develop a UCAV used specifically for the suppression of enemy air defences and deep strike missions. In 1999, Boeing received a contract to build two demonstrator UCAVs and a mission control station; flight testing was scheduled to commence in 2001; it has been indicated that the first flights could possibly even take place in 2000.

Dassault Aviation, France is undertaking UCAV-related study work in cooperation with Boeing. Saab, Sweden also has several ongoing auto-financed UCAV-related studies.

It seems safe to state that UCAVs still have a long way to go before they can enter into service, and that not only technical hurdles have to be overcome, but that a number of ethical and moral issues also have to be dealt with. The current rules of engagement will also have to be adapted to take UCAVs into account.

MILITARY MISSIONS

Currently, both tatctical and strategic UAV missions principally consist of:

- Reconnaissance
- Surveillance
- Target acquisition

Tactical UAVs have already been used to fulfill decoy and radar saturation roles (Allied Forces during Desert Storm); the the case of Israel this was the original purpose of UAVs. BAe Australia's Nulka is to enter service shortly as an anti-ship missile ship-launched decoy.

There are however many other missions that both tactical and strategic UAVs will possibly be used for in the future (*See Figure 11*). To a relatively large degree, the future roles that UAVs will be able to play will depend on the development and production of the payloads required to accomplish the indicated specific missions.

Fig. XI - MILITARY UAV MISSIONS

CURRENT
- Reconnaissance
- Surveillance
- Target acquisition
- Decoy

FUTURE
- Aerial mine detection
- Artillery correction
- Battle damage assessment
- Battlement management
- Comms & data relay
- Command & control relay
- Digital mapping
- Electronic warfare
- Flight path recce
- NBC recce
- Perimetric surveillance
- Psychological warfare
- Radar jamming/saturation
- Remote sensor delivery
- SIGINT
- Target designation
- Treaty monitoring
- Urban warfare
- Offensive :
  - anti-radar
  - anti-vehicle
  - anti-ship
  - anti-structure

IMAGING PAYLOADS

Most of the future UAV missions depend for a large part on the development of the right sensors at the right price. As the cost of UAV missions, in military and financial terms, is very much in function of the required payload sensors, substantial R&D efforts and industry consolidation are taking place in this area. Figure 12 gives an overview of existing imaging payloads and ongoing developments in this area. Figure 13 details non-imaging payloads. Figure 14 details what imaging payloads are currently in use on what UAVs.

Better and Smaller

Advances in technology (e.g. non-cooled IR, hyperspectral imaging and downsized Synthetic Aperture Radar (SAR) sensors) and new detector elements (e.g. 3-5 μ InSb chips, Megapixel FPAs) are permitting ever increasing performance (bigger stand-off distances, higher sensitivity, higher resolution), as well as ever larger degrees of miniaturisation. Substantial advances in the fields of Electro-Optics (EO) and IR sensors have been made, and apparently the miniaturisation of the optics is one of the last remaining challenges. These developments have made it possible to produce relatively small (in weight and dimension) mono and multiple sensor (EO, IR, laser range-finder) payloads, which are becoming the imaging sensors of choice for tactical UAVs.

The increasing interest in regimental/brigade level close range UAVs (e.g. Luna-EMT, Germany, Observer-DERA & Cranfield Aerospace & Tasuma/UK, Pointer-AeroVironment/USA, Vigiplane and Vigilant 2000-Techno-Sud/France) and the rather limited payload capacity of such aerial vehicles is driving manufacturers to develop and produce new lightweight sensors, often incorporating new technologies and very novel concepts.

Fig. XII - IMAGING PAYLOADS

CURRENT
EO
IR (3-5 & 8-12μ)
EO/IR
EO/LRF
IR/LRF
EO/IR/LRF
SAR
SAR/MTI

ONGOING DEVELOPMENTS
IR (3-5μ)
Uncooled IR
Miniature sensors
Micro sensors
Multi-spectral
Down-sized SAR
Miniature SAR
LIDAR
Foliage penetrating radar
Hyperspectral imagers
Large format FPAs
Sensor marinization
Automatic target recognition

Figure XIII
NON-IMAGING PAYLOADS

Active RCS simulation
Communications jammer
Communications relay
Land-mine detection & identification
Sea-mine detection & identification
Radar jammer
Radiation seekers
SIGINT
Dispensors for:
- crowd control devices
- pamphlets
- ordnance
- meteorological sondes
- remote sensors

Synthetic Aperture Radar

Recent developments in hard- and software are permitting synthetic aperture radar (SAR) (with and without moving target indication) to prove their operational value as true all-weather sensors in roles including surveillance, target acquisition, mapping, and treaty verification. Advances in technology will shortly see SAR capabilities expand to include e.g. foliage penetration and mine detection. For the moment, SAR is only operational on the Predator (MALE) UAV, but as developments in this field are customer-driven and all military users require all-weather capability, it will only be a question of time until SAR finds its way onto the smaller tactical UAVs.

The CL289 sensor upgrade programme (Sword: 25 kg), a collaborative programme between Thomson-CSF Detexis and Dornier, Germany, and the development of the Lynx SAR (50 kg), funded and carried out by General Atomics, USA, are prime examples of the ongoing effort to down-scale SAR. It is also of interest to note that the Ministries of Defence of Belgium, Denmark, Finland, the Netherlands and Sweden have all designated SAR as necessary options for future upgrades of their UAVs (purchased and still to be purchased).

Non-imaging Payloads

The non-imaging payloads indicated herewith are currently being designed, developed and evaluated for use on different types of UAVs in a number of countries. Active research and evaluation,

Figure XIV - WHO USES, OR WILL USE, WHAT PAYLOAD ON WHAT UAV ?

DEPLOYING COUNTRY	UAV SYSTEM	UAV SYSTEM MANUFACTURER	PAYLOAD DESIGNAT.	TYPE OF SENSOR(S)	PAYLOAD MANUFACTURERS
Algeria	Seeker II	Kentron, South Africa	Goshawk	EO/IR 2nd gen	Cumulus, South Africa
Belgium	Epervier Hunter	MBLE Défense †, Belgium IAI, Israel & Eagle consort.	AA3-70/6-62 MOSP ?	EO still camera EO/IR	Omera/Thomson, France IAI-Tamam, Israel
Bahrain	Exdrone	BAI Aerosystems, USA	PTZ	EO & EO/IR	BAI Aerosystems, USA
Bulgaria	Vigilant	Techno-Sud Ind., France	unnamed	EO	Techno-Sud Ind., France
Czech Rep.	Sojka III	VTUL a PVO, Czech Rep.	Camelia	IR linescanner	Intertechnique, France
Denmark	Sperwer	Sagem, France	Hesis	EO/IR	Sagem, France
Finland	Ranger	Oerlikon-Contraves, Switzerl	MOSP	EO/IR	IAI-Tamam, Israel
France	CL289 Crecerelle Fox MLCS Hunter Vigilant	Aérospatiale/Dornier Sagem, France CAC Systèmes IAI, Israe& TRW, USA Thomson & Techno-Sud Ind.	KRb8/24D, or Corsaire Sword unnamed Cyclope 2000 unnamed - 445G MK III - Camelia - GlobalScan Mosp 3000 - unnamed - Sophie	EO, or IR linescan SAR/MTI CCD linescanner IR linescanner static CCD (pilot) EO/IR IR linescanner HD EO linescanner EO/IR - CCD - IR	Zeiss, Germany Sagem (SAT), France Thomson/F & Dornier/D SAT, Sagem SAT, France SAT, France Inframetrics, USA Intertechnique, France Cose, France IAI-Tamam, Israel Techno-Sud Ind., France Thomson-CSF, France
Germany	CL289 Taifun Brevel (KZO) LUNA	Dornier & Aérospatiale STN Atlas STN Atlas & Matra EMT, Germany	KRb8/24D, or Corsaire upgrade Taifun Isos 2000 P286D Attica	EO, or IR linescan SAR/MTI imaging radar IR IR + EO	Zeiss, Germany Sagem (SAT), France Dornier/Thomson Daimler-Benz, Germany Zeiss, Germany Zeiss, Germany
India	Nishant Searcher	ADE, Bengalore, India IAI, Israel	? Mosp	EO or IR EO & IR	local production IAI-Tamam, Israel
Indonesia	Fox AT2 Heliot	CAC Systèmes, France	- GlobalScan - Camelia - 445G MK II	- HD EO linscanner - IR linescanner - EO/IR	Cose, France Intertechnique, France Inframetrics, USA
Israel	Scout Searcher Hermes 450S	IAI, Israel IAI, Israel Silver Arrow, Israel	various various MOSP	various various EO/IR	Controp, Israel IAI-Tamam, Israel IAI-Tamam, Israel
Italy	Mirach 20 Mirach 26 Mirach 150	Meteor, Italy Meteor, Italy Meteor, Italy	? ? ?	CCD or IR CCD/LLLCCD/IR CCD/IRLS/Panoramic or High Alt. Camera	AquaTV or Galileo, Italy FIAR/Rank-Pullin/Galileo FIAR,Italy/BAe,UK/Vinten or Vinten/UK
Netherlands	Sperwer LUNA	Sagem, France EMT, Germany	Hesis P286D Attica	EO/IR or EO IR + EO	Sagem, France Zeiss, Germany
Romania	Shadow 600 Vigilant	AAI, USA Techno-Sud Ind., France	445G MK II unnamed	EO/IR EO	Inframetrics, USA Techno-Sud Ind., France
Singapore	Scout Searcher	IAI, Israel IAI, Israel	various various	various various	Controp & Tamam,Israel Controp & Tamam,Israel
South Africa	Seeker Vulture	Kentron, South Africa ATE, South Africa	Goshawk ODS	EO/IR 1st gen EO	Cumulus, South Africa ATE & M-Tek, S. Africa
South Korea	Bijo Harpy Searcher	Daewoo IAI, Israel IAI, Israel	undecided ? MOSP	EO/IR radar seeker EO/IR	undecided ?, Israel IAI-Tamam, Israel
Spain	Siva	INTA, Spain	MKD 400NDP	EO/IR	Tadiran, Israel
Sri Lanka	Scout	IAI, Israel	various ?	various ?	Controp or IAI, Israel
Sweden	Back-Pack Ugglan	Mission Technologies, USA Sagem, France	? unnamed	? EO/IR	? Sagem, France
Switzerland	Ranger	Oerlikon-Contraves,Switzerl.	MOSP	EO, IR, EO/IR	IAI-Tamam, Israel
Thailand	Searcher	IAI, Israel	MOSP	EO, IR	IAI-Tamam, Israel
Turkey	Gnat 750	General Atomics, USA	Model 12	EO or IR	Wescam, Canada
UAE (Abu Dhabi)	Seeker	Kentron, South Africa	Goshawk	EO/IR	Kentron, South Africa
UK	Phoenix	GEC Marconi Avionics, UK	MRT-S	IR	GEC Marconi Avionics
USA	Camcopter Darkstar Dragon Global Hawk Gnat 750 Hunter Outrider Pioneer Pointer Predator	Schiebel, Austria Lockheed & Boeing, USA BAI Aerosystems, USA Teledyne Ryan, USA General Atomics, USA TRW, USA & IAI, Israel Alliant Techsystems, USA Pioneer UAV, Inc/AAI Corp. Aerovironment, USA General Atomics, USA	445G MK III Tesar & CA-236 PTZ Hisar & unnamed 12DL Mosp Ultra 3000 or Pop 100 12DS ? - IRμCam Tesar & Skyball	EO/IR SAR EO linescanner EO SAR/MTI EO/IR EO & IR EO/IR EO/IR EO/IR EO/IR EO IR SAR/MTI 2xEO/IR	Inframetrics, USA Northrop, USA Recon/Optical, USA BAI Aerosystems,USA Hughes, USA Hughes, USA Wescam, Canada IAI-Tamam, Israel FLIR systems, USA IAI-Tamam, Israel Versatron, USA) ? Microcam Corp., USA Northrop, USA Versatron, USA

principally concentrated in the USA, is ongoing relative to the possibility of dispensing various devices from UAVs. This obviously also requires, in some cases, the development of the devices that are to be dispensed.

LAUNCH & RECOVERY

As can be concluded from the classification on the first page of this article, tactical fixed wing UAVs (excluding µ UAVs) can be split into two types :

· aircraft with fixed or retractable landing gear (IAI/Israel, Daewoo/South Korea, Kentron/South Africa, IAI and Silver Arrow/Israel, and the majority of the manufacturers in USA);

· aircraft launched by means of a launcher or RATO (Rocket Assisted Take-Off) and recoverable by parachute, in many cases with the help of airbags (all European systems, ATE/South Africa and a small number of US manufacturers).

LAUNCH SYSTEMS

Fixed or Retractable Landing Gear

The Israeli preference for wheeled UAVs most probably stems from the fact that Israel is a relatively small and narrow country with limited military and financial resources. The distances to its sensitive borders (Libanon, Syria) are relatively short and the Israeli Defence Force (IDF) does not traditionally project its forces far outside the country's borders for an extended period of time (S. Libanon is the exception). The short distance to the Forward Line Of Troops (FLOT) permits the IDF, or the Israeli manufacturer operating UAVs for the IDF, to launch their UAVs from established and secure airfields.

Figure XV - UAV Launch Methods

- **Hand-Launched**
- **Weapon-Launched**
- **Launcher:**
  - **- Bungee cord**
  - **- Hydraulic**
  - **- Pneumatic**
  - **- Atmospheric**
- **Rocket Assisted Take-Off (RATO):**
  - **- Zero-length launcher**
  - **- Mono-vehicle canister**
  - **- Multiple vehicle canister**
- **Landing Gear & Wheels**
- **VTOL**
- **Aerial Launch:**
  - **- from manned aircraft**
  - **- from UAVs**
- **Torpedo or missile tube launched**

The US preference for wheeled tactical UAVs is said to be linked to their strategic requirement to be capable of global power projection on one side, and their desire to limit, as far as possible, the necessary logistical trail (no launchers, no parachutes), and is based on the assumption that overwhelming US military force will permit them to secure the infrastructure required for wheeled take-off and landings, irrespective of where they deploy. Out of all the UAV systems in service in the US, only Exdrone and Dragon UAVs, which are in service with the US Marine Corps, use a launcher. It should however be mentioned that the US military also has substantial experience with RATO for launching their UAVs (Pioneer and Hunter).

The tactical UAVs in the aforementioned countries tend to have fixed landing gear, whereas the larger medium altitude long endurance (MALE) and high altitude long endurance (HALE) UAVs have retractable landing gear. A number of manufacturers have equipped their landing gear with a remote controlled break system.

There is only one European Ministry of Defence (Belgium) that has opted for wheeled tactical UAVs (Hunter B). The single Hunter system procured by the French Ministry of Defence, which is of course also wheeled, should be seen as a one-off purchase of a test system for evaluation of payloads and operational concepts, and not as a system in operational military use.

Obviously, both fixed and retractable landing gear increase the weight of the aerial vehicle. The additional set-back of fixed landing gear is that they increase aerodynamic drag. Retractable landing gear take up considerable volume in the fuselage and the wings, which partially explains why they are used only on larger UAVs.

Some manufacturers have also experimented with launch dollies. These are wheeled trolleys on which the aircraft is placed; the aircraft can then take off under its own power, or in the case of smaller UAVs, the trolley is tracked by a high speed static winch, or even bungee cords. This method has now largely been abanded.

Launcher Systems

MALE and HALE UAVs can of course be launched so far from the FLOT, that the required airfields or roads are not normally a problem.

European, and most other military forces, however generally go out from the assumption that the roads or airfields in their countries, which may be required for launching wheeled tactical UAVs will not always be available to the rapidly moving troops in a war time situation. It is of interest to point out that the Belgian Ministry of Defence is the only European entity that has opted to equip its defence forces with a wheeled tactical UAV (Hunter), and that the Croatian Ministry of Defence has also expressed its preference for wheeled UAVs.

Future joint peacekeeping and multinational military operations, and the exposure of European military to the deployment of wheeled tactical and strategic UAVs by their coalition partners, may possibly influence this stance in the future.

UAV launchers can be divided into various categories:

· Bungee cord launchers (which are now largely being abandoned due to their poor performance in both hot and cold temperatures, the inconsistency in their launching speeds and the impossibility to precisely predefine launch speeds). Bungee cord launchers are, for the moment, still used for a number of small UAVs;

· Pneumatic/hydraulical launchers (Crecerelle, Exdrone & Dragon, Fox MLCS, Phoenix, Ranger, Shadow 200, Sperwer, Ugglan);

· Atmospheric launchers (Vulture, Super Vulture);

· RATO launchers can be divided into 3 types:
  - zero-length launchers (CL289, Harpy, Mirach 26, Pioneer);
  - mono-vehicle canister launch (Brevel, Tucan, Mücke);
  - multiple vehicle canister launch (Taifun).

In a 1998, the Crecerelle bungee cord launcher was replaced by a pneumatic launcher supplied by Sagem, France. In the programmed upgrade of the Mirach 26, the Italian MoD has the intention to abandon the RATO launch method and adopt launch by means of a pneumatic launcher. The Netherlands Army has purchased a pneumatic launcher from Robonic, Finland for the launch of their KD2R aerial targets. The targets services division of CAC Systèmes, France is also using a pneumatic launcher (OKT Norge, Norway) to launch their aerial targets.

In view of the systems mentioned above, it is of interest to note that there is currently only one company spe-

cialised in the design, development and production of pneumatic launchers in Europe (Robonic, Finland). One of the specific features of the Robonic series of launchers is that they can be disconnected easily from their transporting trucks and operated without the truck being present. This is accomplished by lowering four pneumatic legs on which the entire launcher rests and then jacking the launcher up, thereby permitting the truck to drive away from under the launcher frame. This system permits to use the truck for other purposes while the launcher is being used (or in storage).

Sagem, France has purchased the licence rights to the launcher developed by OKT Norge, Norway for the Sperwer tactical UAV and this is now produced in France.

The atmospheric launcher produced by ATE, South Africa is a rather unique system; instead of creating an over-pressure to push a piston, the atmospheric launcher creates a vacuum in a cylinder, which pulls a piston in a sealed cylinder. The advantage of this system is said to be logistical (very few parts are submitted to wear and tear) and operational (aircraft can be launched at sea-level as well as relatively high altitudes).

A special mention should be made of the experience AAI Corp., USA has in the field of ship-launched (RATO – Rocket Assisted Take-Off) fixed wing UAVs. AAI Corp. has been involved with the Pioneer UAV from the onset, and has not only been responsible for the majority of the very many upgrades that have been made over the years, but also gained valuable operational experience during the Gulf War, when they established a forward base in Bahrain from where they serviced and reconditioned Pioneer UAVs, which were extensively launched from land-based bases, as well as from ships. Their ship-launch experience with Pioneer has made it possible for AAI Corp. to develop within a very short period of time, in reply to a requirement of the South Korean Navy, the fixed wing Shadow 400 (range: 200 km), which is ship-launched (by means of RATO) and ship-recoverable (by means of a recovery net on the rear deck).

RATOs have several disadvantages: they are added logistical problem; they pose a flammability hazard; they are rather expensive if not purchased in large quantities; they generate visible exhaust fumes and create a high infrared signature; and lastly, changing the payload on a UAV can implicate the necessity to realign the RATO(s). However, zero length launchers are relatively cheap and they make it possible to launch from confined areas (ships), unprepared terrain, and in the case of canister launch, launch preparations can be kept down to a minimum, which makes for a highly mobile system.

BAI Aerosystems in the USA has produced a pneumatic launcher based using commercial-of-the-shelf rodless cylinders for their Exdrone and Dragon UAVs. This launcher principal was proposed by the US Naval Surface Warfare Center to the US Naval research Lab, which funded the development of such a launcher for their electric Swallow UAV. The US Marine Corps then funded the development of a similar type of launcher for their Exdrones and Dragon UAVs; this launcher has now replaced the former pneumatic launchers, which shot out a steel piston pushing the UAV towards the sky. The flying steel piston was obviously a safety hazard.

Recovery

Recovery by means of parachute and airbag is gaining terrain for tactical systems (Brevel and Tucan and Mücke-STN Atlas/Germany, CL289-Aérospatiale/France and Dornier/Germany, Mirach-26-Meteor/Italy, Phoenix-GEC/UK, Sniper-Silver Arrow/Israel, Sperwer and Ugglan-Sagem/France, Vulture and Super Vulture-ATE/South Africa).

Figure XVI - UAV Recovery Methods

- **Belly-landing**
- **Skid-landing**
- **Net (ship- & ground-based)**
- **Wheel(s) :** - without breaks
  - with breaks
  - with arresting hook
- **Parachute :** - standard
  - parafoil
  - dirigable parafoil
- **Parachute & airbag**
- **VTOL**
- **Aerial recovery**

Several UAV manufacturers have equipped there wheeled aerial vehicles with emergency parachutes (AAI Corp.-Shadow 200 & 400 & 600, Alliant TechSystems-Outrider, General Atomics-Prowler II).

A number of UAV manufacturers (e.g. S-Tec-Sentry, Lear Astronics-SkyEye, Northrop Grumman-Starbird) have experimented with various types of parachutes (ram-air parafoils & dirigeable ram-air parafoils), as well as ram air gliding wings. Air-ram wings have even been experimented with as main wings for pusher engine powered payload vehicles. None of such types of parachutes have as yet been adopted and approved by a customer as a standard means of recovery. It is considered to be mentionworthy that mid-air retrieval of UAVs (and aerial targets) under parachute has had a long history in the USA.

Fixed wing aircraft with landing gear can be equipped with breaks on the landing systems (Shadow 600-AAI Corp./USA, and/or arresting hooks that grab an arresting cable laid out over the landing strip between two reels with mechanical break systems (Searcher- IAI/Israel).

Research is also ongoing to equip VTOL UAVs with a parachute recovery system as a safety option. As the recent accident with the CL327 in Australia has shown, auto-rotation cannot always be counted on. One of the solutions being investigated is to house a safety parachute in a rotor-head compartment, or in a cylindrical compartment in the top part of the rotor shaft.

The Pioneer UAV (Pioneer UAV Inc., USA) is the only UAV with substantial recovery experience using a shipborne (and land-based) net system. Recovering aircraft in this manner on a ship requires either exception operator experience, or an automatic recovery system, which guides the incoming aircraft with a high degree of precision into the recovery net.

For obvious reasons, the MALE & HALE UAVs will continue to be equipped with landing gear, which in some cases may be retractable. Butler Parachute Systems, Inc., USA has designed a parachute system consisting of a rocket extractor, a pilot parachute to provide positive main chute deployment until full line stretch is reached, and a main chute with an extended skirt triconical canopy with drive vents, for General Atomics Aeronautical Systems' Predator MALE UAV (for emergency recovery). Butler has designed and built similar parachute systems for the General Atomics GNAT and Altus UAVs.

The commercial use of UAVs over populated areas in most of the industrialised world, as well as the introduction of military UAVs into civilian airspace, will probably

impose, at least initially a more widespread use of parachute and airbag recovery systems on UAVs for safety purposes.

An All-In-One Concept

The FOX MLCS tactical UAV system (CAC Systèmes, France) is noteworthy for the fact that this compact self-contained air transportable system consists of three aerial vehicles, a pneumatic launcher, a UAV operator station, and an image interpreter station all housed on one single Mercedes-Benz truck. The system requires minimal manpower and can launch from any unprepared terrain; the aircraft are recovered by parachute. This cost-effective type of UAV system can most probably find an interesting market with developing countries, as well as with countries for which air transportability, mobility and rapid deployment are key issues.

Automatic Take-Off & Recovery Systems

It is now generally recognized, that the majority of the UAV accidents take place during the launch and recovery cycles, and that most can be attributed to operator failure. This fact is pushing manufacturers and users alike in the direction of fully automated systems.

A growing number of UAV systems are using automatic recovery systems. Various types of automatic take-off and landing systems exist e.g.: millimetre wave tracking radar and guidance systems (UCARS-UAV Common Automatic Recovery System, Sierra Nevada Corp., USA), a laser radar & video camera (RAPS-RPV Autoland Position Sensor, Swiss Aircraft and Systems Company, Switzerland). UCARS has been developed on initiative of the US Joint Program Office; its development started in 1990 and the system has been successfully used with a variety of UAVs (CL-227, Hunter, Pioneer, Predator). RAPS was originally developed for the Ranger UAV (Oerlikon-Contraves), but is also available to other UAV system integrators. Automatic recovery systems will play a major role for all future shipboard recoveries.

DATALINKS

Datalinks should become a major issue in the near future. Some of the pressing matters that have to be dealt with are: availibility, bandwidth, frequency, interoperability. It is not the objective of this article to deal with this topic in detail. However, it should be noted that this problematic situation has been recognized by NATO and is being addressed by a number of committees.

Figure XVII gives a recapitulation of the datalinks currently used.

POWER PLANTS

One of the most critical sub-systems of UAVs are the engines. The majority of the currently flying UAVs are equipped with two-stroke engines manufactured by:

- Aerrow, Canada
- Hirth, Germany
- Limback, Germany
- Meggitt Defence Systems, UK
- Moto Guzzi, Italy
- Quadra, USA
- Rotax, Austria
- Sachs, Germany
- UAV Engines Ltd, UK

Advanced Electronic Systems, United Arab Emirates (AES) has designed a two-stroke engine, which is being produced exclusively for them by Zanzottera Engines, Italy. These engines equipped the AES aerial targets and UAVs.

Turboshaft engines produced by Allison and Williams in the US are used for UAVs. A limited number of UAVs also uses turbojets produced by Allison/USA, Microturbo/France, Williams/USA.

Substantial R&D has been ongoing for some time now in the field of heavy fuel engines. There are several reasons for the interest in heavy fuel engines:

- they do not pose a logistical problem, as fuel is ready available;
- they do not pose as big a fire hazard;
- logic has it that they would be more robust.

Companies involved in this area include:

- General Atomics, USA
- Sonex Research Inc., USA
- Southwest Research Institute, USA & Evan Guy Enterprises, USA
- UAV Engines Ltd, UK

Eventhough advance has been slow and expensive, it now appears reasonable to assume that heavy fuel engines are indeed feasible and will not take too much longer to be fully validated and market-ready.

CIVILIAN & COMMERCIAL APPLICATIONS

The use of UAVs for non-military purposes is still in its infant shoes. However, there are a number of current applications that are mentionworthy.

By far the most widespread and intense use of commercial UAVs takes place in Japan, where VTOL UAVs are extensively used for crop spraying and fertilizing. The use of these VTOL UAVs falls under the jurisdiction of the Ministry of Agriculture; all the aircraft are remotely controlled by an operator and are restricted to flying in-sight (300 m max. distance from the operator), and at an altitude of less than 150 m. All operators are required to follow an official operator's course and obtain an operator's licence.

Agricultural use of VTOL UAVs is now also being envisaged in South Korea.

The earlier mentioned Aerosonde/Laima low altitude long endurance UAV is another example of the interesting possibilities that UAVs can be put to. It should be of interest to note that, in order to make the use of Aerosonde/Laima viable as a meteorological sensing tool, the cost price of the aircraft clearly had be at a very competitive level. At a unit fly-away price of approximately US $ 35.000, this UAV has met its goal. One wonders if the basic Aerosonde/Laima system could also not be used for other purposes such as remote bacteriological or chemical agent, or nuclear fall-out monitoring. Aerosonde/Laima has been authorized by the Australian Civil Aviation Safety Authority (CASA) to fly meteorological missions over Australian waters. It should be noted that CASA has drawn up specific rules and regulations to make the deployment of Aerosonde possible in Australia.

A substantial number of different UAVs are also being used for special effects in the cinema industry and for publicity purposes, as well as broadcast TV and aerial photography purposes. In this respect the following manufacturers can be cited:

- Aerocam R/C Flying Systems, USA
- BAI Aerosystems, USA
- Envol Images, France
- Moving-Cam S.A., Belgium
- Survey Copter, France

In this field, a distinction should be made between indoor and outdoor UAVs. Outdoors, VTOL UAVs are principally used, and indoors lighter-than-air UAVs seem to be the norm. All these systems are PCM remote controlled.

Figure XVII - DATA LINKS - UAV Systems With Operational Range of > 1000 m

DEPLOYING COUNTRY	UAV SYSTEM	STATUS In Serv.	STATUS On Order	UAV SYSTEM MANUFACTURER	DATALINKS C2 Up	DATALINKS Imagery Down	CIVILIAN APPLIC.
Australia	Aerosonde	◆		Aerosonde Robotic Aircraft			◆
Bahrain	Dragon		◆	BAI Aerosystems, USA			
Belgium	Epervier Hunter B	† 	 ◆	MBLE Défense †, Belgium IAI, Israel & Eagle Cons., Belgium	 C-band	 C-band	
Bulgaria	Vigilant 2000	◆		Thomson & Techno-Sud Ind.,France	S-band	S-band	◆
Denmark	Sperwer	◆		Sagem, France	Ku-band	Ku-band	(◆)
Finland	Ranger		◆	Oerlikon-Contraves, Switzerland	UHF	L/S-band	
France	Fox MLCS Heliot CL289 Crecerelle Hunter Vigilant 2000	 ◆ ◆ 	◆ ◆ ◆ ◆	CAC Systèmes, France CAC Systèmes, France Aérospatiale & Dornier Sagem, France IAI, Israel & TRW, USA Thomson & Techno-Sud Ind.	S-band S-band Not appl. 300-600 MHz C-band S-band	S-band S-band Not appl. 300-600 MHz C-band S-band	 ◆
Germany	CL289 KZO (Brevel) Taifun LUNA	◆ ◆	 ◆ ◆	Dornier & Aérospatiale STN Atlas, Germany STN Atlas, Germany EMT, Germany	Not appl. Ku-band ? 5 GHz	Not appl. Ku-band ? 5 GHz	
India	Searcher Nishant		◆ 	IAI, Israel ADE-Bangalore, India	C-band L-band	C-band L-band	
International Coop. Dvpmt	Brevel Tucan	◆ 		Eurodrone (STN Atlas&Matra)	Ku-band C-band	Ku-band C-band	
Israel	Scout Searcher Hermes 450S	◆ ◆ ◆		IAI, Israel IAI, Israel Silver Arrow, Israel	C-band C-band C/L-band	C-band C-band C/L-band	
Italy	Mirach 20 Mirach 26 Mirach 150	◆ ◆ ◆		Meteor, Italy Meteor, Italy Meteor, Italy	420 MHz L & J-band L & J-band	1500 MHz L & J-band L & J-band	
Netherlands	Sperwer LUNA	◆ 	 ◆	Sagem, France EMT, Germany	Ku-band 5 GHz	Ku-band 5 GHz	
Romania	Shadow 600 Vigilant	◆ ◆		AAI, USA Techno-Sud Ind.	C-band S-band	C-band S-band	 ◆
Singapore	Scout Searcher II Upcoming RFI	◆ ◆ 		IAI, Israel IAI, Israel Undecided	C-band C-band ?	C-band C-band ?	
South Africa	Seeker Vulture	◆ 	 ◆	Kentron, South Africa ATE, South Africa	UHF UHF	C-band C-band	(◆)
South Korea	Bijo Searcher II Shadow 400	 ◆ 	◆ ◆	Daewoo IAI, Israel AAI Corp., USA	C-band C-band C-band	C-band C-band C-band	
Spain	Siva		?	INTA, Spain	UHF	S-band	
Sri Lanka	Scout Ongoing RFP	† 		IAI, Israel Undecided	C-band ?	C-band ?	
Sweden	RPG MK III APID Ugglan	† ◆	 ◆ 	Techment, Sweden Scandicraft Systems, Sweden Sagem, France	L-band L-band C-band	L-band L-band C-band	 (◆)
Switzerland	Ranger	◆	◆	Oerlikon-Contraves,Switzerld.	UHF	L/S-band	
Thailand	Searcher II		◆	IAI, Israel	C-band	C-band	
Turkey	Gnat 750 Upcoming RFP	◆ 		General Atomics, USA Undecided	C-band ?	C-band ?	
UAE-AbuDhabi	Seeker	◆		Kentron, South Africa	UHF	C-band	
UK	Phoenix	◆		GEC Marconi Avionics, UK	Ku-band	?	
USA	Camcopter	◆		Schiebel, Austria	S-band	S-band	◆
USA	Darkstar	†		Lockheed & Boeing, USA	UHF/MilSatCom Ku-band/SatCom CDL/LOS X-band CDL/LOS	Ku-band/SatCom X-band/SatCom	
	Exdrone	◆		BAI Aerosystems, USA	UHF	D-band	
	Global Hawk	◆		Teledyne Ryan, USA	UHF UHF/MilSatCom CDL/LOS Ku-band/SatCom	Ku-band/SatCom X-band CDL/LOS	
	Hunter	†		TRW, USA & IAI, Israel	C-band	C-band/LOS	
	Outrider	†		Alliant Techsystems, USA	C-band	C-band/LOS & UHF	
	Pioneer	◆		Pioneer UAV, Inc/AAI Corp.	C-band LOS & UHF	C-band/LOS	
	Sentry	◆		S-Tec Corp.	S- or C-band	S- or C-band	
	Pointer	◆		Aerovironment, USA	?	?	
	Gnat 750	◆		General Atomics, USA	C-band/LOS	C-band	
	Predator	◆	◆	General Atomics, USA	UHF/MilSatCom C-band/LOS Ku-CDL	UHF/MilQSatCom Ku-band SatCom	

An electric powered lighter-than-air indoor UAV, developed and produced by Envol Images has been used for filming indoor swimming races. This brought an unexpected bonus to the swimming trainers: the top view of evolving swimmers made it possible to distinctly see body movements from a new angle, which resulted in making it possible to correct errors unknown up to that point in time, which in turn made it possible to achieve faster times. Envol Images and Moving-Cam have been supplying aerial imagery services to TV broadcasters, the publicity and cinema industry for a number of years. The Sultan of Oman's birthday parade has been broadcast live in Oman from a VTOL UAV developed and flown by Envol Images. BAI Aerosystems has flown its Javelin over public beaches for local TV stations. In all of these cases, the UAV manufacturer has been operating the system as a service to its customer.
Survey Copter, however, has developed and supplied a substantial number of its VTOL UAV systems to international operators for commercial use in their countries (aerial photography, aerial surveys).

A number of companies are investing the use of UAVs for dull and slightly dangerous mission such as powerline verfication.

The Swedish Wallenberg foundation is financing a research project which will investigate the use of VTOL UAVs for traffic surveillance purposes.

The French Groupe INTRA, an organization specialized in intervening in the case of a nuclear mishap inside and outside of France (which has the highest density of nuclear reactors of any country in the world), operates a fleet of various remote controlled ground vehicles for highly specific tasks. In order to be able to control these UGVs from a safe distance, Groupe INTRA has contracted CAC Systèmes, France to supply a Heliot VTOL UAV to act as an airborne control relay, and double as an airborne surveillance platform.

In the fight against illegal immigrants and drug smugglers, UAVs have been used by the US authorities along the southern border of the USA, and in Columbia.

The South African Air Force operates Seeker UAVs on a regular basis for the South African Ministry of Interior for border control purposes and with the specific task of detecting illegal immigrants, pinpointing them and then making it possible for police forces to intercept such immigrants. The SAAF have also operated Seeker during elections in South Africa to monitor crowds.

In its effort to maintain a balanced game population (in accordance with available food supplies), the South African Kruger Game Reserve, regularly counts the large animals in the park. This is done from helicopters. These same helicopters are also used for culling the animals when there are too many of them. The animals have now learned to hide when they hear a helicopter, and consequently they are ever more difficult to count. The use of UAVs is now being consider to detect and count the larger game.

In several countries the tuna industry has expressed keen interest to use UAVs to survey the ocean surface and track down schools of tuna (which in many cases is currently being done by manned helicopters).

The Baltic Watch project in Scandinavia is looking into the possibility of using UAVs to monitor the Baltic Sea and detect pollution, as well as for search and rescue missions.

High altitude long endurance UAVs of various types are being considered as surrogate low altitude satelites for telecommunications and television relay. As these aircraft will have to stay airborne for extended periods of time (weeks-months) alternative power sources such as solar power (Proteus-Scaled Composites, USA)(Pathfinder-AeroVironment, USA) and microwave power (SHARP-Communications Research Centre, Canada) beamed from the ground have been investigated. Angels Technologies Corp, USA has been announced as the first commercial customer of Proteus, and plans to use the aircraft for broadband microwave communications and cellular telephone networks. The SHARP (Stationary High Altitude Relay Platform) has been reported to highly interest China for cellular telephone networks.

Herewith following is a list of ***non-commercial*** some applications for which UAVs are or could be used or considered. The underlined applications are either already taking place, or are being seriously considered:

Civil Defence Organisations
- disaster area surveys & assessment
- communication relays

Forestry Services
- surveillance of forests / plant growth
- <u>fire control</u>
- mapping

National Weather Service
- atmospheric sampling
- <u>meteorology (hurrican prediction)</u>

National & Regional Meteorology Services
- avalanche control
- temperature & humidity monitoring

Ministry of Agriculture (Fish & Wildlife Authorities)
- agricultural monitoring
- river & estuary surveys / illegal waste disposal
- wildlife tracking & accounting
- <u>mapping</u>
- counter poaching control
- fishing law enforcement

Electricity Authorities
- <u>monitoring nuclear facilities</u>
- hazardous waste dump surveys
- power line verification

Customs Authorities
- <u>counter narcotics control</u>
- <u>counter smuggling control</u>

Ministry of Interior, National & Local Police
- <u>anti-terrorist intervention back-up</u>
- <u>counter narcotics surveillance</u>
- riot control
- crowd control
- border patrol
- area surveillance
- <u>traffic control</u>
- <u>search & rescue</u>
- <u>emergency relief surveys</u>

Postal Services
- urgent package delivery in remote areas

Ministry of Environment
- air sampling
- hazardous waste dump surveys
- <u>forest fire detection</u>
- <u>inshore pollution detection</u>

Ministry of Transport
- <u>traffic & highway surveys & monitoring</u>
- mapping
- dike & dam inspection

Coast Guard
- surveillance for counter narcotics
- <u>illegal alien intrusion detection</u>
- illegal fishing control
- <u>national security threat surveys</u>

- search & rescue missions
- illegal ship's bilge oil dumping control

Civil Aviation Authorities
- noise measuremt for A/C certif. purposes

Red Cross, Red Crescent, NGOs
- natural disaster area surveys & assesment
- mine detection & indetification
- emergency relief surveys
- communication relays
- rapid delivery of emergency supplies

World Wildlife Fund
- rain forest canopy research
- natural reserve surveillance
- wildlife tracking & verification
- poaching control

Research Institutes
- marine environmental research
- meteorolgy research
- atmospheric research
- climatolgy research
- pollution related research

Commercial applications for UAVs can include:

Telecommunications Industry
- telecommunications relay

TV Industry
- pay-for-what-you-watch local TV coverage

News Casting
- news, sports & special events

Publicity Services
- television commercials
- promotional services
- flying publicity
- aerial photography

Cinema Industry
- aerial photography
- special effects

Electricity Distribution
- powerline verification

Real Estate
- aerial pictures for selling property
- aerial surveys

Surveying
- city & suburban planning

Farming & Ranching
- checking cattle
- fence line verification
- crop spraying (pesticide & fertilizer)
- crop monitoring
- soil, moisture & pest monitoring
- insect sampling

Fishing Industry
- monitoring of fishing grounds
- search for fish concentrations (tuna)

Maritime
- monitoring shipping hazards
- search & rescue

Security
- surveillance
- perimeter control

Lumber Industry
- tree spotting
- growth control
- mapping
- fire control
- forestry survey
- log transport

Aerial observation of archeological sites

Oil & Mining Industry
- gas & oil pipeline monitoring
- radiometric airborne surveys for geologic mapping & mineral prospecting
- airborne monitoring of geothermal areas
- airborne magnetic & electromagnetic surveys

Railroads
- aerial monitoring of rail lines & trains

Ski resorts
- avalanche control
- search & rescue

Aeronautical Industry
- testing new airframe configurations & designs

MILITARY CHALLENGES

Subsequent to the Gulf War and more specifically the conflicts in Bosnia and Kosovo, the military forces of the NATO countries, and some non-NATO countries, have realized the importance of information dominance during such crisis periods and the potential offered by UAVs in this respect. The advantages offered by the use of MALE UAVs, and the fact that only the USA has such assets, was not lost on anybody; during these conflicts the European military was to a large extent dependant for its intelligence.

The current politically driven tendancy to aim for zero risk conflicts, as well as the objective of minimal collateral damage and casualties, minimizing fraticide and controlling the electromagnetic spectrum during conflicts, are some of the additional driving factors behind the growing military interest in UAVs, and MALE UAVs with their large stand-off distance in particular. The increase of regional conflicts, and joint or coalition military intervention, peacemaking or peacekeeping operations, along with the building of a European military capacity, is making interoperability a major issue.

To sustain the interest in UAVs, the acquisition and ownership cost of these assets must come down, and this will definately implicate an increasing use of commercial technology. To reach this goal, a closer relationship between the military planners and industry is required; the military should find ways to implicate industry in the system definition phase at an earlier stage than currently is the case, and thereby avoid creating unrealistic requirements and permitting industry to take a phased approach to UAV system development.

The European military now have the major task of updating their UAV requirements to also incorporate MALE UAVs, deciding their operational requirements, evaluating existing systems, defining the required budgets, obtaining the required funding, weighing the interest to develop the required assets (or certain critical subsystems) on a national level, against a multi-national (European) development, and against purchasing the existing Predator system. In light of the current drive towards a European military union, such a decision should preferably be made in consultation with the other European partners. The problems of integrating MALE UAVs, and possibly at a later stage HALE UAVs, with the other military land, sea and space intelligence assets should also not be taken lightly.

Continued and increased use of UAVs in all categories by the military will hinge for a large part on finding solutions to the current problems related to UAV airworthiness and air traffic management. Once again these problems can only be solved, if a cooperative effort is made by the European military authorities and industry, on a national and multi-national basis, implicating as much as possible existing organizations and agencies with expertise in the relative fields.

EVOLUTIONARY MARKET

Today most military UAVs are used in the reconnaissance, surveillance and target acquisition roles. But as has been pointed out in this paper, there is a substantial amount of additional roles they will be fulfilling in the near future.

Between now and 2005 micro UAVs will start to come on steam, intelligent offensive UAVs will start showing up, VTOL UAVs in various categories will see the daylight, the use of UAVs as telecommunications relay will become a more wide spread reality, and many of the current reliability and operational robustness issues will start to be solved. More cost-effective solutions will be found and substantial strides will be made thanks to emerging technologies. Substantial advances should also be made in the fields of UAV-related airworthiness and air traffic management. This will build confidence with the current and upcoming users and should increase the degree of acceptance of UAVs, which should result in new concepts of operation starting to be defined. The coming five years will probably also see an increased use of UAVs for non-military purposes.

During the period between 2005 and 2010 airworthiness and air traffic management rules and regulations should start to firm up, currently emerging technologies should be mature, new rules of engagement should start to see the light, the acceptance of UAVs by users and the general public should start to become reality, armed UAVs should start coming into service, UCAVs should start to become a reality, and there should be an ever increasing use of commercial UAVs. It is envisaged that during this period UAVs will start to be deployed on a substantially larger scale.

UCAVs are expected to become an operational reality around 2020.

INDUSTRY CHALLENGES

In all the aforementioned military and non-military applications and scenarios, UAVs can only be considered as a viable alternative, if industry can successfully tackle the following issues:

Flight in Controlled Airspace

This is the all-conditioning factor. It order to make this possible, the first step is to develop acceptable airworthiness norms. The initiative to develop such norms should go out from industry, in co-ordination with the current military and potential future users. This should be initiated on a national level, and coordinated on a pan-European and worldwide level. It would appear logical that the first step is to form national working groups to deal with this issue and to put in place a structure which will permit the co-ordination of these working groups.

Safety & Reliability

Industry has to clearly demonstrate the safety and reliability of its UAV systems, and its critical subsystems. The current operational robustness has to be improved and ways have to be found to deal with such critical issues as system software evaluation and validation.

Lower Operational Costs

The acquisition price, as well as the operational costs have to be lowered to such a level that UAVs will be competitive with manned aircraft. This will most probably also mean a more intensive use of commercial off-the-shelf components.

Development Funding

Development funding from national governmental and European Union sources should be sought, and a higher degree of international cooperation should be aimed for. The potential spin-offs of UAV-related R&D should be more clearly highlighted to potential investors and goverment authorities. Universities should be more systematically involved in UAV-related research. It could be of interest to investigate the possibility of getting potential future UAV users involved with the financing of R&D at a very early stage.

The possibility of allotting a certain percentage of the government savings generated by downscaling and professionalizing the military forces in Europe to UAV-related research should be investigated. The current European tendancy to decrease Ministry of Defence funding of research and development programmes could cause substantial harm to the future of the European industrial base and widen the technology gap with the USA even further, if it is not reversed. The ongoing industry consolidation in Europe should also contribute to minimalising the national funding of funding of competitive programmes.

Increase Product Awareness

A substantial effort should be undertaken by industry to make the possible future commercial users more aware of the potential offered by UAVs, the technologies involved with their development, and the possible spin-offs. The awareness of UAVS by potential users can be increased by responsible coverage in the specialized and general public press, as well as on television, organizing educational briefings, inviting possible future users to UAV exhibitions and demonstrations, and bringing the issue of UAVs to the attention of technical universities, engineering schools, research institutes, as well as military academies.

Addressing Emerging Demand

Industry will have to adapt to dealing with customers other than the military. The approach to the commercial market is totally different from the military, and industry will have to adjust to be able to deal with potential applications of which it does not have much, or in some cases any, knowledge. This will be a period of bi-directional education, and will require industry to adapt to dealing with non-traditional customers who require relatively small numbers of UAVs. Only then will it be possible to understand the emerging demand.

The creation of a pan-European funded European UAV Institute, along similar lines as CIRPAS in the USA could be of interest to investigate.

A much closer relationship should be created by industry with its traditional military customer(s), with the intent to be involved by the military at a much earlier in the definition of their future operational requirements.

Legal, Ethical & Political Issues

The use of UAVs for many applications, including future military roles such as armed UAVs and UCAVs, will bring with it a necessity to deal with a substantial number of specific issues such as third party liability, operator responsibility, the implications of onboard intelligence with decision-making, and the legal implications of crossing over borders of friendly and non-friendly countries.

Strategic Alliances

It ishould by now be evident that only those companies that form international strategic alliances of one kind or another can hope to be amongst tomorrow's players in the UAV arena. It will be increasingly difficult for any single company to stay in rythm with the advances of technology and be able to auto-finance the development of tomorrow's UAV systems.

Spectrum Management

It is considered imperative that, in view of the limited availibility of frequency spectrum, UAV-related spectrum

management issues will be raised and addressed by European industry on a national, European and international level, with the competent authorities, through the existing organizations and agencies with responsibilities in this field.

Industry/University Partnership

Industry should endeavour to make more and better use of the research potential offered by the European universities. An interesting driver in this area could be the instigation of pan-European inter-university development competitions.

Customer Financing

Industry should endeavour to help find new and innovative ways to finance the purchase of UAV systems by potential military users and commercial operators.

UAV AIRWORTHINESS & AIR TRAFFIC MANAGEMENT

As has been pointed out earlier, the major restraint weighing on the commercial use of UAVs is the lack of airspace regulations, which is directly linked to the absence of internationally acceptable certification (airworthiness) norms relative to UAV systems, system software, sub-systems, and operator training, as well as the absence of regulations concerning command & control and datalink frequencies.

The recent conflicts in Bosnia and Kosovo also forced the military users to take notice of UAV-related air traffic management issues. With UAVs being launched out of Albania, Hungary and Macedonia to overfly Bosnia and Kosovo, posed a number of operational ATM problems, never before encountered in such a conflict. This situation has greatly contributed to focusing attention on UAV-related ATM.

The crucial issue of UAV-related ATM is now being seriously addressed by the civil aviation authorities on a national basis in a number of countries: Australia, Italy, Japan, Switzerland, UK. The Australian and Italian Civil Aviation Authorities have even drawn up a draft regulations for UAVs based on Joint Aviation Authorities' regulations pertaining to Very Light Aircraft (JAR-VLA). The Civil Aviation Safety Authority (CASA) of Australia has taken a risk management approach to the development of regulations for UAV operations, focusing on two areas: certification requirements and airspace requirements. For flights over populous areas, or within controlled areaspace, certification and operating requirements are the most demanding. However, for flights in remote areas, these requirements are relaxed.

The military authorities in Belgium, Denmark, Finland, France, Germany, Italy, The Netherlands, South Africa, Sweden, and UK are also addressing this issues seriously. But in practically all cases, the required rules and regulations are still lacking.

It is of interest to mention that the Royal Netherlands Army Materiel Command imposed the certification of the Sperwer UAV in the contract they signed with Sagem, France. At the time, no UAV airworthiness norms existed and it was made the responsibility of the Royal Netherlands Air Force's (RNAF) to define such norms. Basing themselves on the framework of the Joint Aviation Authorities' airworthiness norms for Very Light Aircraft (JAR-VLA), using their experience in the field of certifying manned military aircraft, and in close cooperation with Sagem, the RNAF has drawn up the world's first detailed UAV airworthiness norms. This ice-breaking process has been rather lengthy (3 years and still going), time-consuming, labor-intensive, expensive, and has necessitated the production of multiple volumes of documents, that were not foreseen at the onset.

NATO's Air Traffic Management Committee is deeply involved with UAV-related issues; the importance of finding an acceptable solution within the shortest possible time-frame, was driven home very strongly during the recent conflicts in Bosnia and Kosovo.

Surprisingly enough, the US FAA has not made any really noteworthy progress in this area, notwithstanding considerable lobbying efforts by US industry and the American Unmanned vehicles Systems Association.

At the recent international workshop on UAV-related air traffic management matters, that was held at EUROCONTROL headquarters in Brussels, Belgium on instigation of NATO, it was agreed that there is a legitimate right for UAVs to operate commercially, and that the non-existance of procedures/requirements for UAV operations should not restrict the development of UAVs. Indeed, the further development of UAVs should encourage and stimulate the development of the appropriate procedures.

EURO UVS' ACTIONS

Advances in the field of UAV-related airworthiness and air traffic management, will have far-reaching effects for current and future UAV operators, as well as industry, and requires a coordinated collaborative effort, involving the civilian aviation authorities, military representatives and industry on a national, European and international level. This fact has now been recognized by a number of organizations and has resulted in the following:

- On 9 June 1999, EURO UVS organized, in cooperation with NATO's Air Traffic Management Committee and in coordination with the Joint Aviation Authorities and EUROCONTROL, for the second consecutive year, an international workshop in Paris, France to deal with the critical topic of UAV airworthiness issues.Subsequent to this workshop, designated UAV Certif, which brought over 100 delegates from 17 countries together, a CD-ROM grouping a substantial number of international UAV-related airworthiness reference documents and opinion papers was produced by EURO UVS.
- On 13-15 October 1999, EUROCONTROL organized, together with NATO's Air Traffic Management Committee, and with the cooperation of EURO UVS, an international workshop on the topic of UAV-related Air Traffic Management (ATM). This event, designated UAV ATM, brought together 158 international military, civil aviation and industry delegates (NATO HQs, EUROCONTROL, Europe's Joint Aviation Authorities, FAA, all European countries, as well as Partnership For Peace states, Australia, and North America).
- UAVS, the United Kingdom's Unmanned Aerial Vehicle Systems Association has been founded by the leading UAV-related manufacturers in UK to deal with UAV-related airworthiness and ATM issues on a national level by liaising closely with UK civil aviation and military authorities.
- EURO UVS has instigated the creation of a French industry working group. WG-UAV/France has the intention to elaborate recommendations for submission to the French CAA (DGAC) relative to

UAV airworthiness issues. The work of this working group will be undertaken in close coordination with French national military and civil aviation authorities.

- EURO UVS is instigating similar working groups in Germany (together with Austria & Switzerland) (WG-UAV/Germany+Austria+Switzerland) and in Scandinavia (WG-UAV/Denmark+Finland+Norway+Sweden) before the end of 1999.
- EURO UVS has the intention to coordinate the activities between the various European working groups, and promote information exchange in this area internationally (Australia, Israel, Japan, North America, South Africa). Unless there is an element of harmonization between the European nations, and on a wider international scale, there is the potential for individual organizations and countries to go their own way and establish positions that may, subsequently, prove irreconcilable.
- After consultation with European military authorities, EURO UVS will be organizing before February 2000 an informal workshop for European military involved with UAVs. The objective of this workshop will be twofold:
  - to bring together European operational military authorities involved with UAVs and create an informal forum where they can exchange ideas and opinions;
  - to endeavour to create a consensus on the European military approach to UAV airworthiness and ATM issues at a very early stage.
- In June 2000, EURO UVS will be organizing, with the sponsorship of the international UAV community,and the participation of European Ministries of Defence, and in coordination with NATO, EUROCONTROL and the JAA, a major international technically informative conference and associated exhibition in the 'Palais de Congrès' in Paris, France. The activities at this event will be:
  - 14 June will be dedicated to reviewing UAV-related airworthiness and air traffic management issues, and will be a follow-up to the 1999 UAV Certif and UAV ATM events. During this day reports will be brought out by the various European working groups on their activities over the last 12 months. At this conference an updated version of the UAV Certif CD-ROM will be made available.
  - 15 June will feature presentations on military tactical and commercial fixed wing, lighter-than-air, and rotary wing UAVs.
  - 16 June will feature presentations on low altitude long endurance, medium & high altitude long endurance, and atmospheric UAVs.

INDUSTRY RECOMMENDATIONS

The general draft recommendations of the UAV ATM workshop held in Brussels (13-15 Oct. '99) were the following:

1- Encourage National Civil Aviation Administrations of the ECAC Members States in coordination with other interested agencies to initiate, where not yet done so, work towards the reviewing of national legal framework with the aim of permitting the safe and economic operation of UAVs.

2- With the view to the ultimate harmonisation of the certification requirements for UAVs to operate in ECAC Member States airpsace, invite EUROCONTROL, through its Airspace and Navigation Team of the EATMP to develop operational requirements for the operational and navigational capabilities of UAVs, and to consider the required ATM procedural and airspace management elements.

3- With the view to permitting UAV operations outside reserved airspace, invite national administrations and interested organizations, in cooperation with air users associations, to carefully study implications on ATS systems developments and airspace capacity.

4- With the view to the ultimate harmonization of the airworthiness and certification standards for UAVs to operate in European member states airspace, invite the JAA through its working arrangements to develop harmonized airworthiness requirements and certification processes.

5- NATO is to define the circumstances under which military UAVs would require to operate outside reserved (segregated) airspace.

6- NATO Document AC/92-D967 - «Guidance for Unlmanned Aerial Vehicles (UAV) Operations, Design Specification, Maintenance and Training of Human Resources» should be validated, updated, expanded and maintained as a useful reference document for further development.

7- To develop cooperation with ICAO in order to improve harmonization and the regional planning process.

8- To develop cooperation with FAA, Civil Aviation Safety Authority of Australia (CASA) and other interested non-European authorities in order to share experience and aim for an early harmonization of the certification requirements.

9- Having regard for the limited availability of frequency spectrum, it is vital that the spectrum management issues raised by the unique operating characteristics of UAVs are addressed. It is recommended that those organizations and agencies with responsibility at national and international levels for spectrum/frequency management be approached with a view to considering the impact that UAVs will have on the global communications infrastructure.

EURO UVS, with its wide base of European active industry and military members, and its constantly growing number of international associate members, hopes to be able to contribute significantly to the process, which will lead to the creation of UAV-related airworthiness and air traffic management rules and regulations. It this respect EURO UVS considers it has a valuable co-ordinating role to play in Europe, and to a certain extent also outside of Europe, in relation to the aforementioned, and welcomes input and suggestions from all concerned parties.

AIRSPACE POLICY AND AIR TRAFFIC MANAGEMENT

UAV System Challenges

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ABSTRACT

The world of manned aviation has been the predominant aerial activity in the skies for the 20^{th} century. The fundamental principle by which the infrastructure and institutional arrangements have been predicated is that there is a man in the loop in the air (pilots) and on the ground (air traffic controllers). With the advent of extremely capable Unmanned Aerial Vehicle (UAV) systems, this will no longer be the case and many assumptions about how aircraft are designed, developed and operated will be challenged. However, in the 21^{st} century this will be an evolutionary process and the organisations that will take it forward are already in place today, to begin the task of providing the necessary frameworks within which UAV systems will co-exist alongside manned aircraft.

The challenges for these organisations include legislation and regulation, airspace policy, air traffic management, airworthiness, certification, communications, command and control. This lecture covers issues relating to airspace policy and air traffic management aspects.

1 INTRODUCTION

1.1 The current framework

The global framework for civil aviation derives from the Convention on International Civil Aviation (Chicago Convention) of 1944 that set the international dimension to aviation, as we perceive it today. Under the auspices of the subsequent International Civil Aviation Organisation (ICAO), views have been developed to cope with differences in aviation's regional growth and complexity.

The European dimension to the management of air traffic has involved a number of organisations. Membership of these organisations is diverse and disparate so that building consensus through any one these organisations has not build consensus at a regional level.

At a national level the International regulations, standards and recommended practices are interpreted and enshrined in legislation or through appropriate measures, this interpretation aspect, has led to national differences. A process of harmonisation in Europe is now however a driving force. There is also a similar harmonisation and convergence occurring between the collective European states and the United Sates on a number of related issues.

In the United Kingdom, which reflects the state in other countries, there is no provision made for either the certification or operation of UAVs. So as things stand today, UAVs must be restricted to danger areas unless specific exemption is given by the Civil Aviation Authority's, Safety Regulation Group. In the UK, MOD policy is to respect the primary statutory document, the Air Navigation Order No. 2 (1996), and so this state of affairs also applies to military UAVs.

The advent of Trade Associations focussing on UAV activities has led to a sharp increase in the level of debate. In the United Kingdom, the stage is now set for greater co-operation between Regulatory Authorities and Industry through the work of the Unmanned Aerial Vehicle Systems Association.

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.

1.2 Sovereignty, legal and regulatory frameworks

key question and still the most crucial today. The focus is both on the nationality of the aircraft and the sovereignty of the airspace. It is a major defence and political issue. It drives to the heart of a country's being and hence has led many organisations, especially in Europe, to have an active role in aviation's development. Much of the sovereignty issues are historic and in Europe this has held up the development of the internal market. This is in contrast to America, where one language, and one large country has had its benefits.

A legal and regulatory framework for aviation has emerged that still adheres to a national regulatory focus but within a global and regional legal framework. This has meant the evolution of regulatory processes that are neither efficient nor globally effective.

The global framework begins with the political framework through the United Nations, and in Europe continues with the Council of Europe and the European Union. Following on from this, other organisations have emerged and evolved to work within these frameworks or to complement them, such as NATO. At the national level the seeds of self-interest always conspire to make any issue that more complicated.

The military have been more nationally driven and by a different set of rules. A pre-requisite for military superiority is uniqueness, since one always wants to have something that the opposition does not. This is counter intuitive to setting up common standards and co-operative agreements. However through such organisations such as NATO standards and co-operation have started to occur as more and more allies train and fight alongside each other. However, the increasing commercial pressure to cut costs appears a greater driver

1.3 Airspace Policy and Air Traffic Management

Airspace policy is about the political framework and the legal framework within which aviation activity occur. In the UK it is also about ensuring that all users have access to airspace to perform their operation, which is is nearly always a compromise. This then leads on to the establishment of a certification and licensing regime which are the strategic pre-requisites for any operations. Air Traffic Management operates within this framework, focussing on ensuring that aircraft movements operate safely and effectively for all concerned. Aircraft operations cover a wide range and because of this a system has evolved to segregate those with different aerial activities. This system covers military and civil operations and can be vastly different from one country to the next.

At the highest level there is the interface between the various countries and the establishment of different flight regions. This leads on to classes of airspace for different kinds of operations and the rules of the air by which pilots must comply. This paper will explore this aspect later.

1.4 The advent of the Unmanned Aerial Vehicle (UAV) System

UAVs are largely undefined and few have really given thought to any definition. In a strategic sense definitions are important. They provide the basis for understanding who should be involved in discussions and who are the stakeholders.

Many organisations may not at first sight have relevance to UAVs but that is probably because it is easy to be blinded by the notion of the man in the loop and its underlying assumptions. Many organisations exist on behalf of members such as the International Air Transport Association who look after the interests of the airline community. Since most airlines are state owned, these kind of organisations are powerful lobbying groups, which may see the UAV as a threat. However, they may be as equally significant in shaping the future processes and direction of the UAV industry and the regulatory framework.

UAVs have up till now largely been constructed and flown on a national basis and then primarily by the military. This has led them to be largely ignored by the global and regional level civil aviation organisations. At a national level the low level of activity has led to flights being individually

sanctioned by the civil or military aviation organisations that deal with certification, licensing and air traffic management.

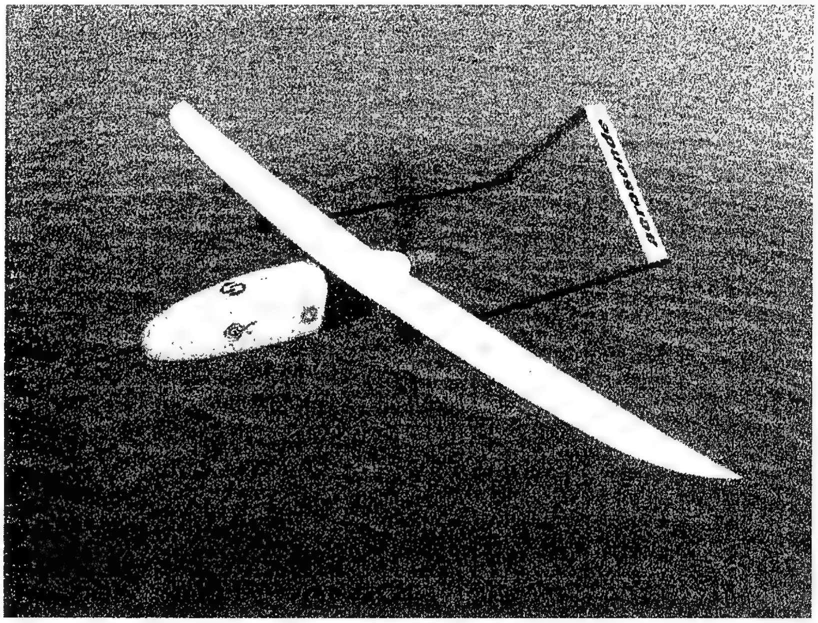

Figure 1 The Aerosonde

The flight of the Aerosonde[1] across the Atlantic was probably the first civil international UAV flight encompassing sovereignty, airspace policy and air traffic management issues. However, the aircraft was not allowed to fly in controlled airspace and the certification of the aircraft was not addressed as there was no way for this to be carried out.

From experience anything that needs to occur in a five-year timeframe in the aviation industry is tactical and only beyond this can one truly start to think of strategic directions and evolutions.

The big issue is that most people's current perception of UAVs is limited to the tasks that they have been allowed to undertake e.g. military surveillance and reconnaissance, local camera photography etc. Once it is realised that UAVs could be freight carriers and travel internationally, then it becomes apparent that many organisations should be interested in their development.

2 INDUSTRY AND THE INSTITUTIONAL BACKGROUND

2.1 The Birth of International Civil Aviation

The Second World War accelerated the technology required to fully realise an international civil aviation industry. There was also the expectation of a favourable end to the war and this led 54 states to convene in Chicago on 1 November 1944 to lay down the rules for what was to be a fast growing industry. The outcome was the Convention on International Civil Aviation or Chicago Convention (appendix B), the legal framework upon which all subsequent air transport industry development has been based.

The international organisation created as a result of the convention was the International Civil Aviation Organisation (ICAO) which came into force in 1947 with its headquarters in Montreal, Canada where they are still located today. ICAO is a specialised agency of the United Nations. It sets standards and recommended practices in 17 areas, including Air Traffic Services and Aeronautical Telecommunications. It also recognises nine geographical regions, which must be treated individually for planning air navigation facilities which include Europe and North America.

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[1] A 13 Kg, 3 metre span unmanned aircraft called Aerosonde successfully flew across the Atlantic in 26 hours landing on August 21st 1998. It was a civilian flight organised by the INSITU group who are looking to develop UAVs for meteorological observations over the ocean.

The aim of ICAO is to *"foster the safe and orderly development of international air transport service on the basis of equality of opportunity and social and economical operations."* The key element from the Chicago Convention, that is still very relevant today, is that it makes a specific guarantee of sovereign rights in the air. The Americans had wanted an "open sky" policy to be adopted but instead the now famous six freedoms were established and the Americans had to accept that there could be no stable commercial activity without some kind of reciprocity.

The most important bi-lateral agreement was the Bermuda Agreement of 1946 between the United States of America and Great Britain. Its main feature was the formula of granting reciprocal rights to designated carriers. The capacity and frequency levels were left to the operators, subject to vague guidelines. This formed the blueprint for all bi-lateral agreements among ICAO member states.

The Convention also recognises the right of any state to insist that air services within its own territory or designated by it in bilateral air services agreements on international routes should be operated by airlines which are *"substantially owned and effectively controlled"* by its own nationals.

As the top organisation in the international aviation community , ICAO sets Standards and Recommendations (SARPs) in all areas. Most notably Annex 8 to the convention contains those SARPs related to airworthiness, Annex 10 those related to Air traffic Systems and Annex 11 covers Air Traffic Management issues.

Among ICAO's more recent significant achievements has been the development of a satellite-based system concept to meet the future communications, navigation, surveillance/air traffic management (CNS/ATM) needs of civil aviation.

In December 1944 the chief executives of 19 state owned airlines convened. The result was the birth of the International Air Transport Association (IATA). Whereas ICAO is a forum for national governments, IATA functions as the international air transport industry's link with governments and the public. It is the world parliament of the airlines and their representative in international organisations.

In both its organisation and its activity, IATA has been closely associated with ICAO. For the airlines, IATA provides machinery for finding joint solutions to problems beyond the resources of any single company. For governments, IATA helps co-ordinate international rates and fares, and to facilitate the fast and economical transport of airmail. For the public, IATA ensures high standards of efficient operation everywhere.

There is no doubt that air transport is a dynamic force in our modern world. From 1944 to 1989 the number of passengers carried rose from nine million to over one billion, a hundred-fold increase. Airfreight, which did not exist in 1944, has now become an essential component of world trade.

2.2 The Regional Dimension in Civil Aviation

The two great nations at the end of the Second World War were America and Great Britain, the latter albeit in a severely weakened state. America had by this time a thriving aviation heritage upon which to build and a burgeoning internal market, which allowed it a freedom of operation, which could not be duplicated in Europe. Europe was, and still is, a collection of many nation states constantly in flux and driven by many differing national identities.

An intergovernmental organisation set up in Europe in 1948, was the Council of Europe which includes a wider range of countries than the European Union (EU) discussed later. It is mentioned here for completeness and as a political forum should not be confused with the European Council of the EU. It is still in operation today.

Europe in recovering from economic devastation after the Second World War did not at first address its unique development problems in a collective manner. In 1955, 2 years before the birth of the European Community (EC), the European Civil Aviation Conference (ECAC) was formed. Its objective is to review generally the development of European air transport so as to promote the co-ordination, the better utilisation, and the orderly development of air transport, and to consider any special problems that may arise in this field. It is in this respect that it has extended its influence in recent years to cover Air Traffic Management issues.

Recommendations adopted by ECAC are aimed at the harmonisation of policies of its member states, usually with regard to co-operation between their airlines, charter operations, fares and rates. Currently there are 37 member states in ECAC and they are represented by their Directors General of Civil Aviation. The special problem of European air traffic congestion led in 1987 to ECAC involving the relevant Transport Ministers.

On 13th December 1960, the International Convention relative to co-operation for the Safety of Air Navigation laid the foundation for the formation of Eurocontrol in 1963. The aim of Eurocontrol is to provide a variety of air traffic services for member states at their request. Eurocontrol's functions encompass those that are not perceived as threatening to the sovereignty of individual states. This aspect makes it complimentary in many ways to ECAC, which is a political forum.

All European Airlines that run scheduled services belong to an organisation known as the Association of European Airlines (AEA). Unlike IATA that has far greater industry responsibilities, the AEA has little part in enabling change. Despite this it has been an outspoken critic of national governments' responsibilities for dealing with the airspace infrastructure problems within Europe. In particular it has criticised the European Union for not harmonising the skies over Europe.

2.3 The Regional Military dimension

Although the world of aviation is largely being shaped by civil requirements, the military still have extensive operations. Many exercises and routine operations are carried out between Nations. The most notable international organisation in dealing with military issues is the North Atlantic Treaty Organisation (NATO).

The North Atlantic Treaty was signed in Washington on 4 April 1949, creating an alliance of 12 independent nations committed to each other's defence. Four more European nations later acceded to the Treaty between 1952 and 1982.

The North Atlantic Treaty has continued to guarantee the security of its member countries ever since. Today it has been restructured to enable it to participate in the development of co-operative security structures for the whole of Europe. It has also transformed its political and military structures in order to adapt them to peacekeeping and crisis management tasks undertaken in co-operation with countries that are not members of the Alliance and with other international organisations.

NATO's North Atlantic Council established the NATO Committee of European Airspace Co-ordination (CEAC) in 1955. This filled an important gap in International co-operation since military aspects were excluded from the charter of ICAO. NATO (CEAC) is a joint Civil/Military organisation examining Airspace Planning within Western Europe.

2.4 The European Union

On 25 March 1957 the Treaty of Rome was signed by France, Germany, Italy along with the Benelux countries, Belgium, Netherlands and Luxembourg which subsequently brought the European Community of six into being on 1 January 1958. This formed what was basically a Free Trade Area and was the first step towards integration. The European Union (EU) as it is now called, consists of five main bodies, the Council of Ministers, the European Commission, The European Parliament, The European Court of Justice and the Economic and Social Committee. The main element in the Treaty of Rome expresses the need to develop a single common market.

A common transport policy document has been produced but there is along way to go in making it effective in Europe. Ministers have since turned to the frail Air Traffic Control Infrastructure and the European Commission has been active in trying to influence civil aviation's evolution. This has been resisted by many countries, arguing that there were organisations in a much better position to effect change.

2.5 The European Aviation Context

The first thing one comes to realise about how institutional arrangements operate within Europe, is that no one forum contains all the required member states to effect a change. Europe from an outsider's point of view looks fragmented and so do its institutions. Figure 2 shows the EU and the main aviation organisations in Europe. It clearly shows the different memberships and how no one forum can be looked at in isolation.

Following on from what has been said previously, there is a close link between the certification of an aircraft and the ability to fly in different airspace, in different countries. However the degree of consensus that looks possible within the JAA on airworthiness issues, is far less than could be achieve by Eurocontrol on air traffic management matters.

The consequence of this is that most countries prefer to operate at a national level as far as possible. In fact in many cases the legal frameworks are different. However the power of the EU comes to bear in that its member states are governed by the same laws, i.e. EU European Law. These gives great powers to the EU to effect change over its member states through directives and regulations.

The problem that arises is that differences build up between nations depending on whether they are members of this or that organisation. The key behind the EU and now behind the JAA and Eurocontrol, is harmonisation. This is both in terms of standards and in terms of operations.

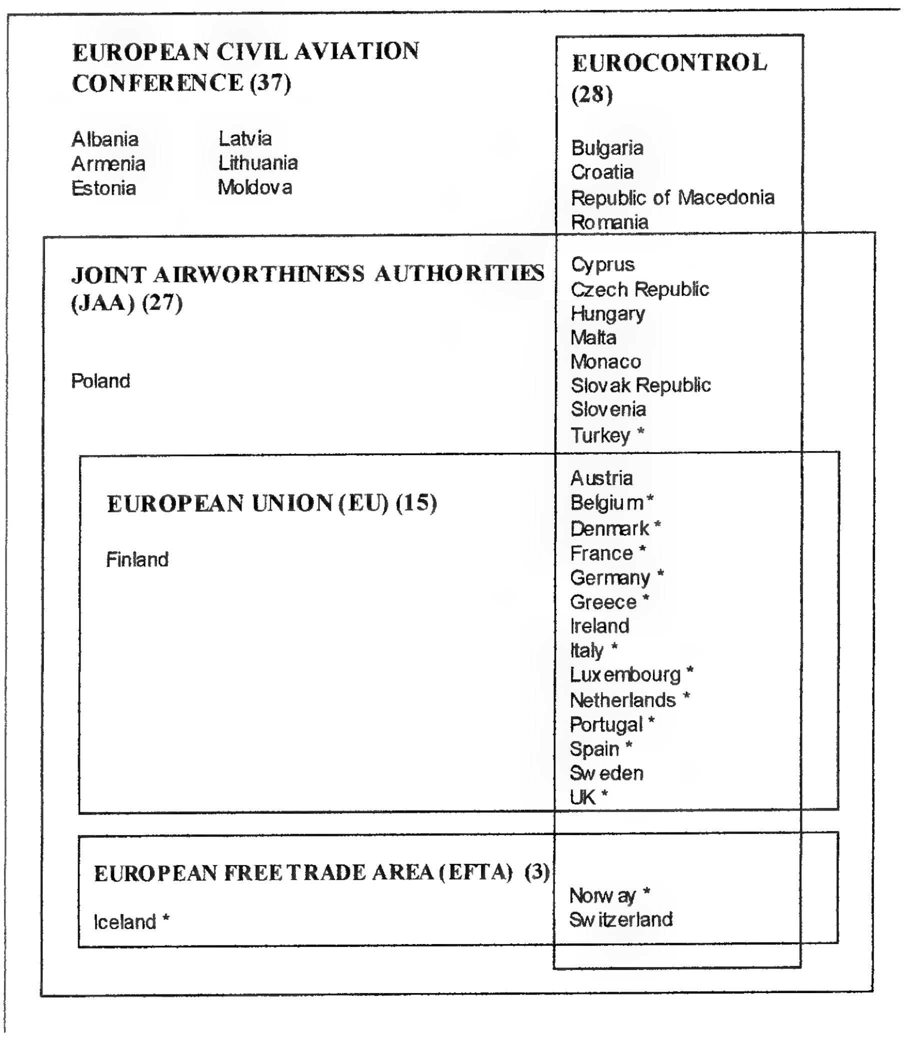

Figure 2 - European Institutions and their membership
(those states marked with * are also in NATO along with Canada and the United States)

NATO has also been promoting harmonisation of standards through its STANAGS, however it only has 16 member states and concentrates more on military issues.

The most successful forum for effecting change has been ECAC. It has the most number of members and because of this has taken a greater role than it was originally set up to undertake, in all aspects of aviation's evolution.

2.6 The American influence

The picture is not complete unless the American influence on the world of Aviation is taken into account. Being the biggest economy in the world, it has also developed the biggest aviation industry in the world.

The main relevant organisation is the Federal Aviation Administration (FAA) which has a similar role to the Civil Aviation Authority in the UK.

The FAA's mission, is to improve the safety and efficiency of flying. For the first time commercial space launch operations have come under FAA, and a new range of issues from safety to competitiveness will be addressed. Because the U.S. aerospace industry is active worldwide, FAA has a global perspective, expanding with the addition of its commercial space functions. Government Administration and Congress mainly direct the FAA.

FAA's major functions are to:

- Develop, operate, and maintain a safe, productive, and efficient national air traffic management system
- Ensure a national air traffic management system which is in harmony with a safe, secure, efficient worldwide system
- Regulate and encourage aerospace safety and security
- Protect the public from aircraft noise
- Assist and promote development of airports and the U.S. aerospace industry
- Promote U.S. aerospace industry vitality

The FAA has a number of bi-lateral agreements with countries such as Canada and the UK regarding the harmonisation of airworthiness standards and is active in trying to bring together the European Joint Aviation Requirements (JARs) and its own FAA Airworthiness Requirements (FARs). In ATM terms it has the largest commercial and military aviation activity and so the FAA has great influence in the world.

2.7 A National Viewpoint

As an example of a national view (figure 3), the United Kingdom sits inside this global and regional framework and has nationally based organisations capable of interpreting and administering all the various regulations and directives from all these institutions (Table 1). It is not surprising therefore that problems arise and different interpretations occur between countries

Perhaps the first thing to be understood is that it is the Governments of Member States that are members of these forums and not their agencies. So the United Kingdom National Aitr Traffic Systems Limited is not a member of Eurocontrol, it is the UK government that is the member.

The Civil Aviation Act (1982) provides the CAA with wide ranging powers to deal with all aviation matters, even the legal power to impound aircraft for the non-payment of navigation charges. The other main Statutory Instrument is The Air Navigation Order 1995 (ANO).

The ANO is amended by an Act of Parliament. If a need for an amendment should arise, the CAA develops and proposes changes to the legislation but does not have the power to actually amend the

legislation. However, the CAA has been given a discretionary power to impose requirements on the basis of being satisfied as to the competence of any applicant for a certificate or a licence.

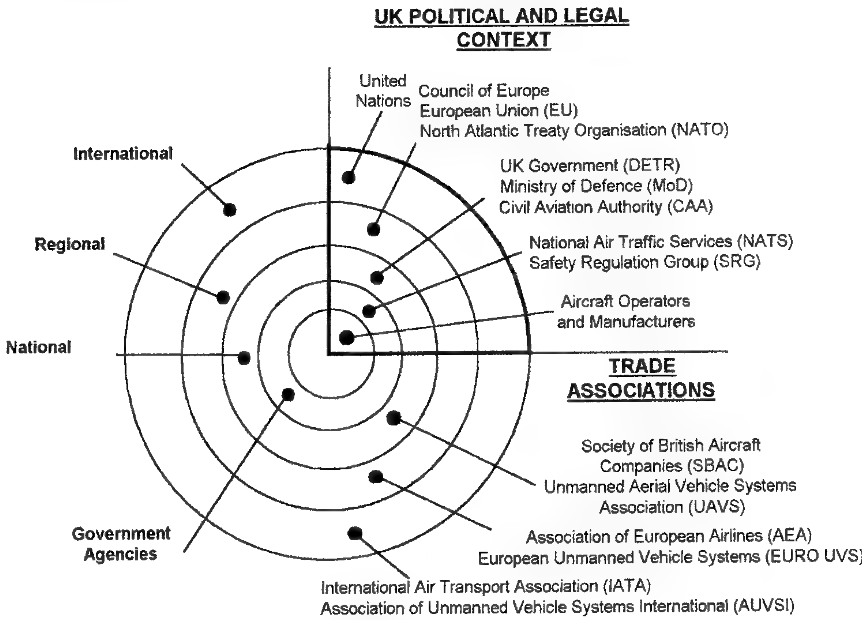

Figure 3 - UK Political and Legal Context for Aviation

ICAO	Standards and Recommended Practices (SARPS)
EU	Directives and regulations
JAA	Joint Airworthiness requirements (JARs)
EUROCONTROL	Air Traffic Management Standards

Table 1 – Main documents to be used and interpreted at national level

The ANO contains sections on::

- Registration and Marking of Aircraft
- Air Operators Certificate
- Airworthiness and Equipment of Aircraft
- Aircraft Crew and Licensing
- Operation of Aircraft
- Fatigue of Crew
- Documents and Records
- Movement of Aircraft
- Air Traffic Services
- Aerodromes, Aeronautical Lights and Dangerous Lights

So although the aviation industry has global and regional perspectives, national governments maintain tight control over what can actually be carried out in any particular country.

3 AIR TRAFFIC MANAGEMENT CONCEPTS AND PROGRAMMES

3.1 ICAO CNS/ATM Concept

ICAO is a driving force in Air Traffic Management (ATM) at a global level, and ATM is covered by a set of ICAO SARPS referred to in Annexes 10 and 11 of the Chicago convention. ICAO also has set up the arrangements whereby certain states are allowed to operate ATM services over some Oceanic regions. So for instance, the Shanwick Oceanic area which is basically the North Eastern Atlantic, is given over the United Kingdom to operate while the Gander FIR in the North Atlantic West region is given to Canada to operate.

However, the most significant achievement for ICAO in ATM terms is in the development of a satellite-based system concept to meet the future communications, navigation, surveillance/air traffic management (CNS/ATM) needs of civil aviation.

CNS/ATM, formerly known as the future air navigation systems (FANS) concept, is essentially the application of today's high technologies in satellites and computers, data links and advanced flight deck avionics, to cope with tomorrow's growing operational needs. It will make obsolete much of today's expensive ground-based equipment, which uses line-of-sight technology and has inherent limitations. It will also produce economies, efficiencies and greater safety. But it is not these characteristics that make it a new frontier for aviation. It will be its impact as an integrated global system with consequential changes to the way air traffic services are organised and operated.

The CNS/ATM systems concept, which has received the endorsement of ICAO Member States, is now in its implementation phase. This major task includes the development of standards, recommended practices and guidance material that will be applied well into the 21st century. From a UAV perspective this is probably the most significant enabling area in ATM.

3.2 European Air Traffic Management

The European Civil Aviation Conference (ECAC) is the body responsible for the full range of civil aviation matters in Europe in the family of United Nations organisations. It has a particularly close relations with ICAO which also has a regional office in Paris, in the same building as ECAC. ECAC brings together the top officials dealing with international aspects of aviation from each of its member states. There are 37 European member countries of ECAC which puts ECAC in a unique position.

Back in 1987 ECAC took the decision to take a major development interest in air traffic control matters because at that time the escalating scale of delays was getting worse and becoming a subject of major political attention across Europe. It appeared that while there were many ATC projects, nobody was co-ordinating it, politically. Eurocontrol was only co-ordinating a relative small number of European countries and could only do a certain amount. The ICAO regional office in Paris was developing new systems for the next century related to the Future Air Navigation System (FANS) that was being developed on a global basis with a European focus in what is termed the Future European Air Traffic System (FEATS). ICAO was not focused on the immediate to medium term growing air traffic problem within Europe and National administrations were making their own improvements but no one was communicating effectively with each other.

There was a co-ordination role required and ECAC decided to take this on. That has meant working not only with each of the other national Air Traffic Control (ATC) administrations but with a lot of other organisations that are involved in ATC to a greater or lesser degree. ECAC has no particular expertise of its own in air traffic control. It is a very small organisation in terms of numbers of staff. It was trying to bring together all the available resources, national resources and all the other bodies, under one common political hat rather than these resources being dissipated.

On one side ECAC has to work closely with ICAO, the Commission of the European Communities in Brussels, and Eurocontrol. It also has to work with the CEAC , the NATO body that concerns itself with the NATO side of the civil / military interface in air traffic control. On the other side ECAC has contact with the airlines, IATA and the AEA. All of these bodies were brought into the team in order to move

forward. The reason that ECAC could succeed where other organisations might fail was that it had the largest membership of any organisation in Europe, 22 in 1987 that has increased to 37 in March 1998.

The complexity of organisational memberships in Europe has already been mentioned, however the most dominant member states are France, Germany and the UK. The result of these complex relationships is that compromises are difficult to achieve because of conflicting interests but tend to be more binding when attained.

ECAC has in the past addressed air transport liberalisation, environmental, noise and jet engine emission types of issues. However in 1988 it held its first meetings on ATC issues. The success that ECAC has had in stimulating initiatives to tackle ATC issues has been fortuitous for the EU. Whilst the small membership of the EU could afford minimal cohesion for the ATC problems, its continuing economic influence compliments ECAC. In recognition of this ECAC is now undertaking less work within its economic committees. ECAC has a policy to co-operate with the EU, since the EU has legislative and financial abilities that ECAC does not have.

ECAC is also moving away from dealing with the majority of technical matters and concentrating on their policy implications. This will see it dealing less directly with ATC problems in Europe in the future. One area that it will concentrate on is those issues relating to environmental policy such as engine emissions. The EU on the other hand is moving towards having a greater involvement.

3.3 The ECAC Initiatives

The ECAC initiatives, to tackle air traffic capacity problems, can be viewed as occurring in three stages (table 2). The first was to get the best out of existing systems, the second was to improve en-route capabilities and the third to improve the airport air traffic system.

The first aim was to get a more orderly approach to the management of traffic in those busiest areas combined with what's called the European Co-ordination Team (ECT). A fire-fighting team of people from national administrations with air traffic expertise from all round Europe, directed by Eurocontrol, who in broad terms can at a particular air traffic control centre brainstorm on how to fix problems. They were able to target in on places where there are problems that a broader expertise can help with.

Work	Date adopted	Associated Programmes
European Co-ordination Team & Flow Management	Initiated 1988	CMFU Central Flow Management Unit
En Route Air Traffic System Strategy	Adopted 24th April 1990	EATCHIP European Air Traffic Control Harmonisation & Integration Project
Airport Air Traffic System Strategy	Adopted 17th March 1992	APATSI Aiport Air traffic Systems Interface

Table 2 - ECAC Initiatives

Work towards a Central Flow Management Unit (CFMU) was initiated, under the control of Eurocontrol. Flow control is effected when the number of aircraft in any particular airspace sector becomes greater than the capacity of that sector. There is a knock-on effect to other sectors with the result that aircraft waiting on the ground at Heathrow may be waiting for airspace to be free in Greece, a truly European problem. The CFMU has now centralised all the separate flow management units within Europe, so that flow control is now more effective and the best use is made of the available airspace.

The CFMU is only a crisis tool. It is required for the peaks in air traffic demand so ECAC next set about looking at the strategic ATC issues. The first issue here was the fragmented upper airspace and its division along national boundaries. Although the issue of sovereignty and Article 1 of the Chicago Convention could not be tackled, making sure that adjacent Air Traffic Control Centres could communicate effectively and seamlessly as far as the airspace user was concerned, could be tackled. The

inability of even the best equipment in individual states to communicate freely with equipment in other states because none of it was designed for that purpose, led in part to the European Air Traffic Control Harmonisation and Integration Project (EATCHIP) project managed by Eurocontrol.

On the 13th March 1992, the ECAC ministers met in London to agree a new strategy for airports. The overall objective is to improve the potential throughput of European airports and their surrounding airspace while maintaining safety and respecting the environment.

3.4 EATCHIP Flexible Use of Airspace

The EATCHIP project put forward the concept of the flexible use of airspace. This states that airspace should no longer be designated as either purely civil or military airspace, but rather considered as one continuum and allocated according to user requirements. Any airspace segregation should be temporary, based on real-time usage within a specific time period.

It puts forward three levels of management as in Table 3. There is a sub-group called the Flexible Use of Airspace Subgroup, which has discussed the operation of UAVs and it is this group that will probably be the European focus for further work, which is supported by NATO (CEAC).

Level	**Aim**
1 Strategic	Establishment of pre-determined airspace structures
2 Pre-tactical	Day-to-day allocation of airspace according to user requirements
3 Tactical	Real-time use of airspace allowing a safe Operational Air Traffic/General Air Traffic separation

Table 3 - Flexible Airspace Management Levels

It is important to remember that the role of Eurocontrol regarding EATCHIP is to manage the Programme. The States, as providers of Europe's Air Traffic Management infrastructure, are responsible for the implementation of harmonised measures and the operation of integrated Air Traffic Control systems. The problems that arise is that each State implements at a different speed and in some cases at a different level.

3.5 Eurocontrol ATM work and the European Commission

Eurocontrol now has greater organisational and co-ordinating capabilities than it did in the early 1990s as it moves forward. It has also started a major consolidation of its different programmes under the umbrella strategy called ATM 2000+. Eurocontrol is also progressing the ICAO CNS/ATM strategy.

A paper, produced by the European Transport Commissioner, Neil Kinnock, and entitled, “Freeing Europe’s Airspace”, is part of a continuing story, in the European Commission’s quest for greater powers over European Air Traffic Management.

The main theme of the paper is the call for Eurocontrol to be made into a powerful regulatory authority. This centralist approach is not new since in August 1989, the Association of European Airlines (AEA) put forward a radical idea that was backed by the European Commission of privatising Europe’s air traffic control centres into a single pan-European holding company with pan European responsibility. Everyone else opposed this.

The paper suggests that the shortcomings in Europe for ATM are :-

- a fragmented overall picture
- lack of decision-making mechanisms
- lack of decision making aids
- inefficient use of available resource
- lack of means of following up decisions

- lack of tools for implementation and support
- inadequate cost control

In answer to these, the paper puts forward the need to bring together all the elements necessary to develop a comprehensive European ATM policy, effective decision-making processes based on majority voting, stronger support for decision makers, encourage managerial responsibility of ATM providers and stimulate their cost-consciousness plus a central authority.

So far, the paper has been rejected and it remains to be seen if the European Union will continue with this particular line.

3.6 NATO CEAC and NAFAG

Since 1991 NATO members and other European countries have held meetings on the civil/military co-ordination of air traffic management periodically, with high-level participation. In May 1992, the Central and East European and Central Asian states, which are members of the North Atlantic Co-operation Council (NACC), took part in a seminar on this issue, together with representatives from NATO countries, as well as the NATO Military Authorities and five international organisations with responsibilities in this field.

From November 1992, co-operation Partners were invited to take part in plenary sessions of the CEAC addressing the civil/military dimension of the integration of Central and Eastern Europe in Western European air traffic management strategies. Regular plenary and working level meetings now constitute part of the co-operation activities related to air traffic management foreseen in the NACC Work Plan.

Early in 1994 European neutral countries were invited to participate in CEAC activities, thereby establishing the committee as a unique forum for co-ordination between civil and military users of the entire continental European airspace, as acknowledged by the European Civil Aviation Conference. The Partnership for Peace initiative agreed by NATO's Heads of State and Government in January 1994 is further increasing concrete co-operation in this area, notably with regard to co-ordination of air exercises.

In 1992 NATO Naval Armaments Group (Project Group 35) recommended that an ad hoc working group be established to draft advisory guidelines for the air traffic management of UAV operations outside prohibited, danger or restricted areas. The aim of this working group is to provide advisory guidelines for UAV operations which individual nations can use as a framework for developing their own regulations and procedures if and when they decide that such operations are practicable.

A document was produced in December 1997, outlining guidelines for their operation, design specification, maintenance and training of human resources. Interestingly the definition for a UAV in the guidelines is " An unmanned recoverable aircraft, which is remotely and fully controlled by means of a pilot in command".

NATO has several groups within it but one that is of particular interest is the Air Force Armaments Group (NAFAG). This has two sub-groups that have special interest in UAVs. NAFAG Air Group 1 addresses airborne vehicles (manned and unmanned) and weapons interoperability seeking co-operation in research, development and production.

The Special Working Group on "Future Less-Manned Aerospace Operations" whose mission is to explore the potential for less manned aerospace operations. It is assessing the possible use of unmanned systems to perform military roles and functions for the complete scope of aerospace mission areas and to identify potential impacts on national and NATO forces,.

With CEAC, NATO Naval Armaments Group and NAFAG all with UAV interests, and NATO's role in the EATCHIP flexible use of airspace sub group, there will undoubtedly be developments in the near future in this area.

3.7 The FAA Free Flight Concept

The dream of being able to fly wherever you want has moved a step closer with the concept of free flight. This has great relevance for future UAV operations. An RTCA Select Committee has come up with the following definition:

"A safe and efficient flight operating capability under instrument flight rules (IFR) in which the operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorised flights through special use airspace, and to ensure safety of flight. Restrictions are limited in extent and duration to correct the identified problem. Any activity which removes restrictions represents a move towards free flight."

It is envisaged that to make free flight work effectively a much greater degree of computer assistance will be required by controllers. This will inevitably continue the trend from "man in the loop" to "computer in the loop". The meaning here is that where at present the deciding factor is a human decision making process, the trend will be towards a computer decision making process as the complexity of aircraft intention and interaction goes beyond the intellectual, spatial, computational and temporal capability of the human controller.

There are differences in how the FAA and Europe view Free Flight which basically stem from the better ground infrastructure within Europe and some of the densest airspace. The consequence of this is that the USA are keen on much shorter timescales in moving forward to free flight. According to Eurocontrol, things that come under the free flight banner in the US are what Europe is doing with the EATMS (European Air Traffic Management System) concept.

On March 15 1996, the FAA endorsed an RTCA task force report into Free Flight and in accepting the report stated that 13 out of 37 near term recommendations would be actioned in the timeframes set out by the report. The remaining 24 would be carried forward with a redirection of FAA resource and greater participation from the user community as appropriate.

The acceptance of such a move towards a new concept in the US means that the differences between the US and Europe on the way forward could be diverging. In Europe the large investment in ground based infrastructure; navigation aids, radar and ground communications, tends to influence strategy formulation and decision making processes.

The most striking thing in the RTCA recommendations is that greater use of Satellite voice and data communications, plus VHF and HF datalinks is envisaged, but nowhere does the word radar appear. Phrases like GPS instrument approach procedures, GPS based route structure and GPS altimetry, all point to a greater dependence on what is best described as the Space segment, which will augment the ground and air segments in use today.

The recommendations point to a number of developments that could significantly alter the role of air traffic control providers. Free Flight suffers from various levels of uncertainty such as short-term knowledge of intent, no directional altitudes (i.e. flying at certain heights when on certain headings) and cruise/climb without specific clearance. In this context, predicting sector density becomes an issue. So rather than talking of a sectors capacity one talks about what if N aircraft are in a sector at the same time, each with the uncertainties listed above. This leads on to procedures about the separation of responsibilities between pilots and controllers under different traffic densities and procedures for handing over responsibility.

One way forward is to transfer to the cockpit a greater understanding of what is around it, appropriately put as, “greater situational awareness”. This is probably essential when the sectors themselves may be deployed dynamically as a means to facilitate free flight operations. For UAVs this presents difficulties as there is no man in the cockpit.

4 AIR TRAFFIC MANAGEMENT OPERATIONS

The prime motivation behind any form of air traffic control is safety. Controllers must therefore keep the aircraft they handle safely separated using internationally-agreed standards. This is achieved by allocating different heights to aircraft or by arranging certain minimum horizontal distances between them. These distances vary according to circumstances, but aircraft flying along the airways under radar surveillance, for example, are kept five nautical miles apart horizontally or at least 1,000 feet vertically.

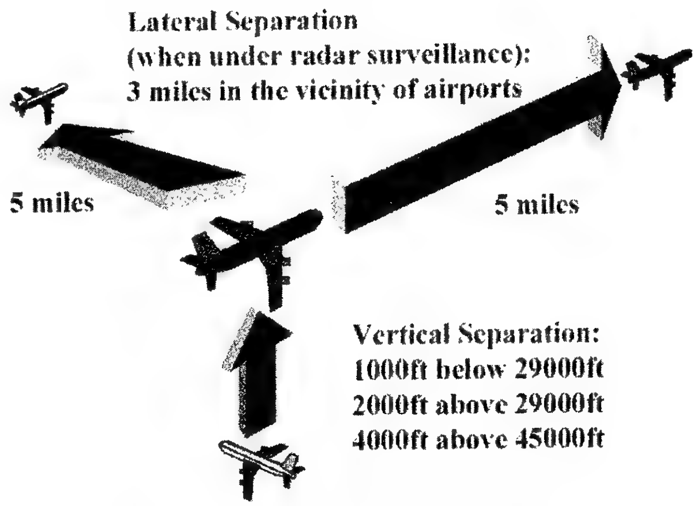

Figure 4 Aircraft Separation Standards

Within the airspace, a network of corridors has been established. These corridors, or airways, are usually ten miles wide and reach up to a height of 24,000 feet from a base of between 5,000 and 7,000 feet. They mainly link busy areas of airspace known as terminal control areas which are normally above major airports. At a lower level are the control zones which are established around each airport. The area above 24,500 feet is known as upper airspace. All these areas are designated "controlled airspace" and aircraft fly in them under the supervision of air traffic controllers. Pilots are required to file a flight plan for each journey containing details such as destination, route, timing and height.

Within controlled airspace, pilots must follow controllers' instructions; outside controlled airspace they take full responsibility for their own safety although they can ask for assistance. In fact, military controllers, who work closely with their civilian colleagues to provide a fully integrated service to all users, offer an air traffic service to aircraft in uncontrolled airspace. Military personnel also provide services to aircraft crossing airways and for those flying above 24,500 feet. A priority task for them is aiding aircraft in distress.

Aircraft in the initial or final stages of their journey are managed by controllers at the airport itself. When aircraft join the airways system, responsibility for handling them passes to colleagues working at the appropriate area control centre. A flight through their airspace could pass through several "sectors" of airspace, each managed by a different team of controllers.

Controlled Airspace is as the name suggests, subject to stringent rules that cover a number of aspects. To fly in controlled airspace the aircraft must be suitably equipped, the crew suitably qualified and the operation of the aircraft must be flown in a manner which complies with the Air Pilot.

In controlled airspace an aircraft must usually carry a radio, a transponder for secondary surveillance by radar, and suitable navigational aids. The aircraft must file a flight plan as depicted in figure 8, which is fed into the ATM system. Flight plans can be filed up to six months in advance as most scheduled airlines do. Provided the necessary changes are made, UAVs on pre-planned flights should not find a difficulty with adhering to this regime.

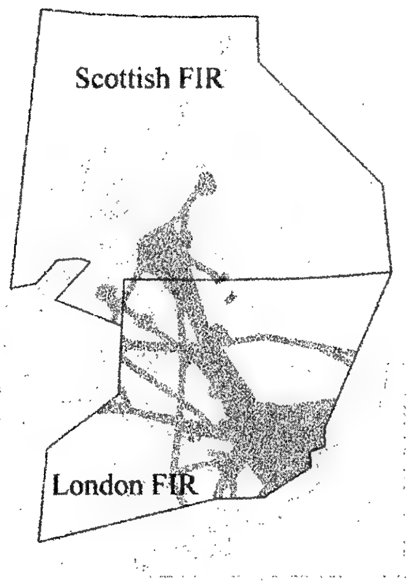

Figure 5 - UK Sovereign Airspace

Aircraft that fly in uncontrolled airspace are not subject to the same rules. They operate generally on the "See and avoid" principle. For manned aircraft this is done by the pilot, for UAVs, there is some difficulty in understanding how this could be done. Much of the difficulty that lies ahead will be focussed on the safety to third parties, in the air and on the ground, in the event of a failure of a UAV. The whole process will be a confidence building exercise based upon the responsible members of the UAV community as it develops. The military provide a number of services in uncontrolled airspace such as the Lower Airspace Radar Service.

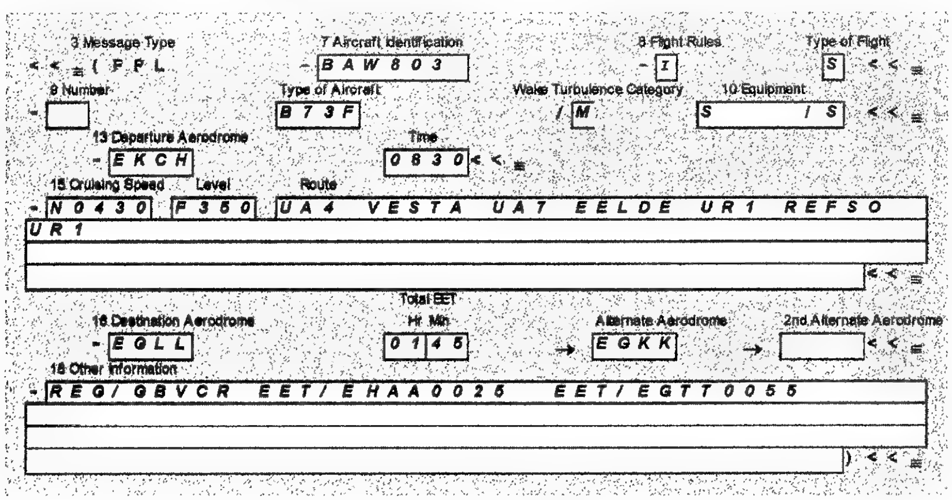

Figure 6 Flight Plan

The control of an aircraft from take-off, through its en-route phase to landing is depicted in figure 9. The number of different scenarios that must be catered for in any ATM environment appears limitless as different aircraft operations are accommodated.

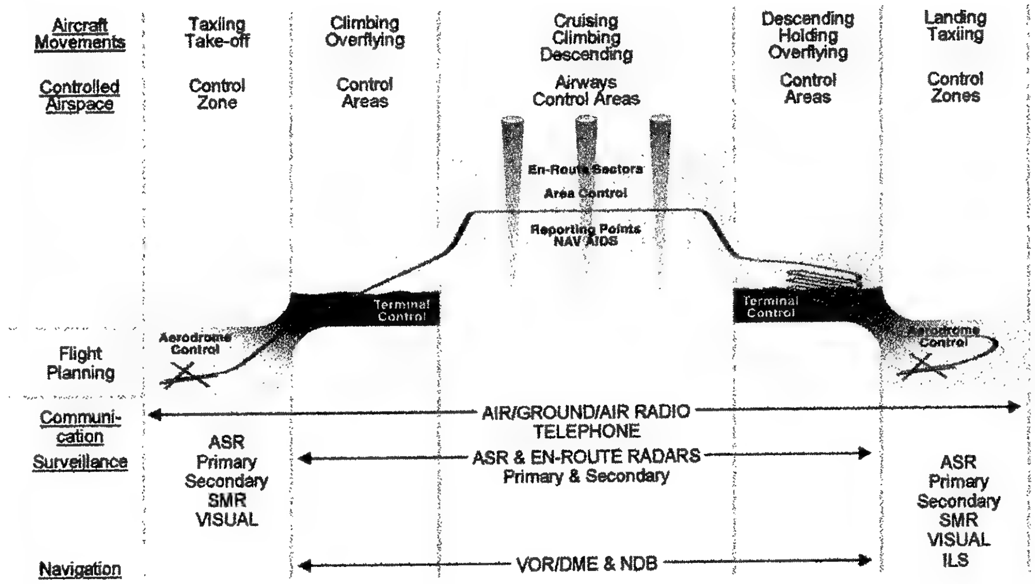

Figure 7 Typical Flight Profile

The picture is somewhat more complicated than this, since figure 9 does not illustrate the different types of aircraft and the different types of operations. To ensure some uniformity around the world, ICAO has set standard designations for the different types of airspace. Class A airspace is that used mainly by commercial traffic such as the major airlines and tends to be airways. The designations both determine the aircraft fit and the flight profiles that are to be expected.

For the UAV the main aspect to be realised is that the whole of the Airspace structure and the Air Traffic Management environment, has been developed for manned aircraft. All the rules have been written around the assumption that there is both a man in the cockpit and a man on the ground in terms of an air traffic controller, or that there are two pilots trying to avoid each other in the "See and avoid" principle.

5 CURRENT POSITION AND IMPLICATIONS FOR UAVs

5.1 The Current UK Position

There is no International or European position on UAVs. The following position on establishing requirements for UAVs in the United Kingdom is based on a letter written by the Civil Aviation Authority's legal department, a workshop held in London at the RAF Club in June 1998 and discussions with various government departments. Much of this will be similar to other national situations and serves to highkight the main issues.

The Air Navigation (No 2) Order 1995 contains a number of provisions for the regulation of aircraft. The main requirements are that any aircraft must be airworthy, which must in the case of an aircraft registered in the United Kingdom be evidenced by a certificate of airworthiness or a permit to fly issued by CAA. The aircraft must carry an appropriate number of licensed flight crew. In the case of public transport operations, the operator must hold an Air Operator's Certificate. When flying, the aircraft must comply with the Rules of the Air.

From the outset there is little understanding given to the needs of UAV flight operations. The Order does however include exceptions for small aircraft. A small aircraft is defined in the Order as any unmanned aircraft weighing not more than 20 kg. In this case, none of the above main requirements apply and a set of conditions are included at Article 76A of the Order subject to which small aircraft

may be flown without complying with airworthiness or flight crew licensing requirements, or with the Rules of the Air.

The rules for "small aircraft" have been principally developed for the purposes of regulating recreational model aircraft flying. The conditions include a prohibition on flight in controlled airspace or within an aerodrome traffic zone, unless in either case the permission of the air traffic control unit has been obtained, a normal maximum height of 400 ft above the surface and a prohibition on flight for the purposes of aerial work (commercial work) without the specific permission of CAA.

5.2 The Safety of UAVs

In order to be satisfied that UAVs may be safely operated, the CAA state that the following issues need to be considered:

- The airworthiness of the aircraft
- Safety in the air
- Maintenance
- Pilot" qualifications

Airworthiness Requirements: To qualify for a certificate of airworthiness the aircraft must be of a type that has been granted a type certificate. This requires the design to be shown to comply with the appropriate design airworthiness code and the organisation responsible for the design and the manufacture to have appropriate CAA approval. The organisations designing and building an aeroplane have to be suitably approved and the design has to be shown to comply with a set of requirements. Permits to fly may be issued without these requirements having been satisfied and it can allow some less onerous design requirements e.g. home built aircraft, microlights. Permit aircraft are not normally allowed to be used for commercial purposes.

Safety in the Air: There are three aspects to this:

- how to integrate UAVs with other traffic when flying within airspace subject to air traffic control;
- how to reconcile the unmanned nature of the vehicle with the principle of see and be seen on which collision avoidance is based outside controlled airspace and which is reflected in Rule 17 of the Rules of the Air;
- how to comply with the low flying Rules when the basic Rules (not closer than 500 ft to any person, vessel, vehicle or structure and not below 1500 ft over a congested area) require the "pilot" to have knowledge of the terrain over which the UAV is flying.

Pilot Qualifications: To achieve the same sort of safety of a manned aircraft some requirements have to be established for qualification of persons piloting the UAV.

Operational Control: Flight Manuals may be required containing all the necessary limitations and operating procedures.

5.3 Exemptions

A UAV which weighs more than 20 kg is not a "small aircraft" for the purposes of the ANO so that all the requirements referred to above (certificate of airworthiness or permit to fly, licensed flight crew, Rules of the Air) must be complied with. In practice of course a UAV cannot comply with these requirements so that the only way such a large UAV may fly is if CAA is prepared to issue an exemption under Article 116 of the ANO. If it is desired to operate a UAV that weighs less than 20 kg outside the restrictions contained in Article 76A, an exemption is also required. The possibility of exemptions does not however offer any real assistance. In order to be satisfied on the question of equivalent safety so as to be able to grant an exemption, many of the fundamental problems would need to be solved.

5.4 FAA Approach

FAA issues special authorisations for civil operations of unpiloted vehicles and the conditions appear similar to the ones used by the CAA. They are on a one-off basis. Some machines are flying beyond the direct view of the operator subject to two criteria. If outside controlled airspace, FAA require the use of a chase plane. If inside controlled airspace above 18,000 ft, operation of UAVs is permitted without a chase plane and out of direct line of sight providing the vehicle is fitted with a transponder which the ATC controller can interrogate and a global positioning system and the RPV controller is in communication with ATC.

The FAA ARAC UAV Working Group has published advisory circulars. These deal with the vehicle design, operational aspects, maintenance and the training of the operator/pilot.

5.5 Military position

Current UK Policy is that military UAVs are confined to Danger Areas (Reserved Airspace). If the MOD really wanted to operate UAVs outside of danger Areas within the UK without complying with the ANO or Rules of the Air it could as the following extracts from the ANO show:

- ANO Article 115 (3) - 'nothing in this Order shall apply to or in relation to any military aircraft
- ANO Article 118 - 'Military aircraft' include the naval , military or air force aircraft of any country and
    a) any aircraft being constructed for the naval, military or air force of any country under a contract entered into by the Secretary of State; and
    b) any aircraft in respect of which there is in force a certificate issued by the secretary of State that the aircraft is to be treated for the purposes of this Order as a military aircraft.
- ANO Article 74(3) (c) - It shall be lawful for the Rules of the Air to be departed from to the extent necessary: ...for complying with Military Flying Regulations (Joint Service Publication J318) or Flying Orders to Contractors (Aviation Publication 67) issued by the Secretary of State.....

At present there does not appear to be any move by the military to change its policy despite the provisions made in the ANO.

5.6 Some further implication for UAVs

Once it is recognised that there is really no well defined framework within which UAVs can operate effectively, the question arises as to what must be put forward to regulatory Authorities to enable them to start changing the legislation. The following are suggested headings

- Definition of a UAV
- Types of UAV
- Types of Operations for UAVs
- Ownership of a UAVs
- Airworthiness of UAVs
- Air Traffic Management of UAVs

The most obvious problem that UAVs face at the outset is the definition of what a UAV is. The fact that there is no one on board means that even filing a flight plan has its difficulties as programmes that verify such plans may require the "person on board" box to have a figure in it. Once a definition is set and is recognised fully, then existing systems can start to be modified to make allowances for the differences.

UAVs come in many sizes and capabilities and will continue to do so. A UAV with a Trans-Atlantic capability that weighs only 13Kg cannot be expected to be treated as a commercial airliner.

Equipment standards for UAVs could become prohibitive if flexibility and understanding are not employed. In operational terms, the use of ICAO airspace designations are based on the assumption of manned aircraft being those that frequented controlled airspace. However, UAVs are probably best served by being controlled in such an environment.

The operator of a civil aircraft usually determines its country of origin. However, the concept of a UAV airline which runs UAV flights in many areas of the world, could put a completely different view on ownership. This type of issue is one of international law and the accepted view that prevails.

Solutions to the above areas are almost a pre-requisite before one can discuss airworthiness and Air Traffic Management issues.

Up until now aviation has separated the concerns of airspace management and airworthiness. For a UAV it is system worthiness that is the crucial issue. The systems in both the static sense, i.e. the ability of air, ground and space components to carry out their function and the dynamic sense, the operation of the total system in real-time against some defined criteria.

There are many issues that arise, most notably the radical shift of direct control. This occurs either by transferring control to a ground controller or to the UAVs software. The "man-in-the -loop" moves from the air to the ground and even into the software development process itself.

From an international perspective it is unlikely that there will be major moves forward in airworthiness or ATM terms due to the many organisations that must come together and understand the various issues. From a European perspective, the situation is not much better however there may be hope at the national level.

6 CONCLUSIONS

6.1 Institutional Framework

The International and European institutional framework for aviation is in a process of constant change. The main international organisation, ICAO, continues to be the top level organisation from which Standards and Recommended practices are disseminated however it is in their interpretation that major problems arise.

At the European level there are numerous organisations each with a different emphasis and historical purpose. Any progress at the UK national level would assist the formulation of positions at a Regional and International level, providing a common set of principles can emerge.

At the outset it must be recognised that there is already a current manned environment based on a set of current concepts which contain the wisdom of decades of development. Any future UAV requirement must be viewed in the context of this environment. There is also an underlying set of assumptions and beliefs that this environment has been built upon, the most notable of which is the concept of the "man-in-the-loop".

The whole international, European and National basis for air transport, air vehicle certification and Air Traffic Management is far from being a seamless, integrated and cohesive area. It is the product of many countries, many organisations and many aviation group interests, constantly seeking to move things in the direction each sees as the best way forward.

The evolution of aviation in the world will continue this way for many years to come and so it is important to maintain a view on the current and possible future impact of all the different organisational influences.

Unmanned Aerial Vehicles or UAVs, have been developed largely in a regulatory vacuum, whether viewed at an international, regional or national level. No regulations have directly addressed their unique capabilities and it has been left to national regulatory authorities to interpret as best they can existing regulations, originally develop for the manned aviation world.

6.2 The future process

There is always risk associated with human endeavour and until operational requirements and operational concepts are defined, the analysis of risk will not be possible. The main process that is required for UAVs today is a risk reduction process, one that enables manufacturers and operators to work towards providing adequate evidence of a safe system.

The Unmanned Aerial Vehicle Systems Association formed in November 1998, now provides the UAV industry in the UK, with a focal point and a means to liaise, lobby and defend UAV interests on a national level.

The main aim must be to present the UAV industry as a competent and responsible community both from a military and civil perspective.

APPENDIX A RELEVANT AVIATION ORGANISATIONS AND COMMITTEES

International Organisations

IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ITU	International Telecommunications Union
NATO	North Atlantic Treaty Organisation
	Committee for European Airspace Co-ordination (CEAC)
	NATO - Ad Hoc Working Group (AHWG) on UAVs
	NATO - Air Force Armaments Group (NAFAG)
	NATO - Army Armaments Group (NAAG)
	NATO - Industrial Advisory Group,Project Group 53 NIAG PG53
	NATO - Naval Armaments Group, Project Group 35 (NNAG PG35)

European Organisations

AECMA	Association Européen des Constructeurs de Matériel Aerospatial
ECAC	European Civil Aviation Conference
EU	European Union
EUROCAE	European Organisation for Civil Aviation Equipment
EUROCONTROL	(Organisation for the Safety of Air Navigation)
	Flexible Use of Airspace Committee
JAA	Joint Airworthiness Authorities

American Organisations

FAA	Federal Aviation Administration
RTCA Inc.	(Radio Technical Commission for Aeronautics) Inc.

UK Organisations

CAA	Civil Aviation Authority
DAP	Directorate of Airspace Policy
	UK UAV Steering Group
DETR	Department of Environment, Transport and Regions
	Air Accidents Investigation Branch (AAIB)
DTI	Department of Trade and Industry
MOD	Ministry of Defence
	Joint Airworthiness Committee 9 - Sub-Committee No 31 (UAVSSC)
	Military Air Traffic Organisation (MATO)
	Tri-Service UAV Steering Committee (TUSC)
NATS	National Air Traffic Services Limited
SRG	Safety Regulation Group

UAV Specific Organisations

AUVSI	Association of Unmanned Vehicle Systems International
EURO UVS	European Unmanned Vehicle Systems Association
UAVS	Unmanned Aerial Vehicle Systems Association

APPENDIX B CHICAGO CONVENTION

Significant articles from the Convention on International Civil Aviation (Chicago, 1944)

PREAMBLE

WHEREAS the future development of international civil aviation can greatly help to create and preserve friendship and understanding among the nations and peoples of the world, yet its abuse can become a threat to the general security; and

WHEREAS it is desirable to avoid friction and to promote that co-operation between nations and peoples upon which the peace of the world depends;

THEREFORE, the undersigned governments having agreed on certain principles and arrangements in order that international civil aviation may be developed in a safe and orderly manner and that international air transport services may be established on the basis of equality of opportunity and operated soundly and economically;

Article 1 : Sovereignty

The contracting States recognise that every State has complete and exclusive sovereignty over the airspace above its territory.

Article 2 : Territory

For the purposes of this Convention the territory of a State shall be deemed to be the land areas and territorial waters adjacent thereto under the sovereignty, suzerainty, protection or mandate of such State.

Article 3 : Civil and state aircraft

(a) This Convention shall be applicable only to civil aircraft, and shall not be applicable to state aircraft.
(b) Aircraft used in military, customs and police services shall be deemed to be state aircraft.
(c) No state aircraft of a contracting State shall fly over the territory of another State or land thereon without authorisation by special agreement or otherwise and in accordance with the terms thereof
(d) The contracting States undertake, when issuing regulations for their state aircraft that they will have due regard for the safety of navigation of civil aircraft.

Article 3 bis *

(a) The contracting States recognise that every State must refrain from resorting to the use of weapons against civil aircraft in flight and that, in case of interception, the lives of persons on board and the safety of aircraft must not be endangered. This provision shall not be interpreted as modifying in any way the rights and obligations of States set forth in the Charter of the United Nations.

(b) The contracting States recognise that every State, in the exercise of its sovereignty is entitled to require the landing at some designated airport a civil aircraft flying above its territory without authority or if there are reasonable grounds to conclude that it is being used for any purpose ,consistent with the aims of this Convention, it may also give such aircraft any other instructions to put an end to such violations. For this purpose, the contracting States may resort to any appropriate means Consistent with relevant rules of international law, including the relevant provisions of this Convention specifically paragraph (a) of this Article, Each contracting State agrees to publish its regulations in force regarding the interception of civil aircraft

(c) Every civil aircraft shall comply with an order given in conformity with paragraph (b) of this Article. To this end each contracting State shall establish all necessary provisions in its national laws or regulations to make such compliance mandatory for any civil aircraft registered in that State or operated by an operator who has his principal place of business or permanent residence in that State. Each contracting State shall make any violation of such applicable laws or regulations punishable by severe penalties and shall submit the case to its competent authorities in accordance with its laws or regulations.

(d) Each contracting State shall take appropriate measures to prohibit the deliberate use of any civil aircraft registered in that State or operated by an operator who has his principal place of business or permanent residence in that State for any purpose inconsistent with the aims of this Convention. This provision shall not affect paragraph (a) or derogate from paragraphs (b) ad (c) of this Article.

Scheduled air services

No scheduled international air service may be operated over or into the territory of a contracting State, except with the special permission or other authorisation of that State, and in accordance with the terms of such permission or authorisation.

* Adopted on 10 May 1984. This amendment will enter into force when ratified by 102 states

Article 7 : Cabotage

Each contracting State shall have the right to refuse permission to the aircraft of other contracting States to take on in its territory passengers, mail and cargo carried for remuneration or hire and destined for another point within its territory. Each contracting State undertakes not to enter into any arrangements which specifically grant any such privilege on an exclusive basis to any other State or an airline of any other State, and not to obtain any such exclusive privilege from any other State.

Article 9 : Prohibited Areas

a) Each contracting State may, for reasons of military necessity or public safety, restrict or prohibit uniformly the aircraft of other States from flying over certain areas of its territory, provided that no distinction in this respect is made between the aircraft of the State whose territory is involved, engaged in international scheduled airline services; and the aircraft of the other contracting States likewise engaged. Such prohibited areas shall be of reasonable extent and location so as not to interfere unnecessarily with navigation. Descriptions of such prohibited areas in the territory of a contracting State, as well as any subsequent alterations therein, shall be communicated as soon as possible to the other Contracting States and to the International Civil Aviation Organisation.

b) Each contracting State reserves also the right, in exceptional circumstances or during a period of emergency, or in the interest of public safety, and with immediate effect, temporarily to restrict or prohibit flying over the whole or any part of its territory, on condition that such restriction or prohibition shall be applicable without distinction of nationality to aircraft of all other States.

Article 37 : Adoption of international standards and procedures

Each contracting State undertakes to collaborate in securing the highest practicable degree of uniformity in regulations, standards, procedures, and organisation in relation to aircraft, personnel, airways and auxiliary services in all matters in which such uniformity will facilitate and Improve air navigation.

Article 38 : Departures from international standards and procedures

Any State which finds it impracticable to comply in all respects with any such international standard or procedure, or to bring its own regulations or practices into full accord with any international standard or procedure after amendment of the latter, or which deems it necessary to adopt regulations or practices differing in any particular respect from those established by an international standard, shall give immediate notification to the International Civil Aviation Organisation of the differences between its own practice and that established by the international standard. In the case of amendments to international standards, any State which does not make the appropriate amendments to its own regulations or practices shall give notice to the Council within sixty days of the adoption of the amendment to the international standard, or indicate the action which it proposes to take. In any such case the Council shall make immediate notification to all other states of the difference which exists between one or more features of an international standard and the corresponding national practice of that State.

Article 44 : Objectives

The aims and objectives of the Organisation are to develop the principles and techniques of international air navigation and

to foster the planning and development of international air transport so as to:

(a) Insure the safe and orderly growth of international civil aviation throughout the world;
(b) Encourage the arts of aircraft design and operation for peaceful purposes;
(c) Encourage the development of airways, airports, and air navigation facilities for international civil aviation;
(d) Meet the needs of the peoples of the world for safe, regular, efficient and economical air transport;
(e) Prevent economic waste caused by unreasonable competition;
(f) Insure that the rights of contracting States are fully respected and that every contracting State has a fair opportunity to operate international
(g) Avoid discrimination between contracting States
(h) Promote safety of flight in international air navigation;
(i) Promote generally the development of all aspects of international civil aeronautics.

Article 54 : Mandatory functions of Council

The Council shall:

(a) Submit annual reports to the Assembly;
(b) Carry out the directions of the Assembly and discharge the duties and obligations which are laid on it by this Convention;
(c) Determine its organisation and rules of procedure,
(d) Appoint and define the duties of an Air Transport Committee, which shall be chosen from among the representatives of the members of the Council, and which shall be responsible to It;
(e) Establish an Air Navigation Commission, in accordance with the provisions of Chapter X;
(f) Administer the finances of the Organisation in accordance provisions of Chapters XII and XV
(g) Determine the emoluments of the President of the Council;
(h) Appoint a chief executive officer who shall he called the Secretary

General, and make provision for the appointment of such other personnel may be necessary, in accordance with the provisions of Chapter XI;

(i) Request, collect, examine and publish information relating to the advancement of air navigation and the operation of international! air services, including information about the costs of operation and particulars of subsidies paid to airlines from public funds;

(j) Report to contracting States any infraction of this Convention, as well as any failure to carry out recommendations or determinations;

(k) Report to the Assembly any infraction of this Convention where a contracting State has failed to take appropriate action within a reasonable me after notice of the infraction;

(l) Adopt, in accordance with the provisions of Chapter VI of this Convention, international standards and recommended practices; for convenience, designate them as Annexes to this Convention; and notify all contracting States of the action taken;

(m) Consider recommendations of the Air Navigation Commission for amendment of the Annexes and take action in accordance with the provisions of Chapter XX;

(n) Consider any matter relating to the Convention which any contracting State refers to it.

Article 62 : Suspension of voting power

The Assembly may suspend the voting power in the Assembly and in the Council of any contracting State that fails to discharge within a reasonable period its financial obligations to the Organisation.

CHAP XVI JOINT OPERATING ORGANISATIONS AND POOLED SERVICES

Article 77 : Joint operating permitted

Nothing in this Convention shall prevent two or more contracting States from constituting joint air transport operating organisations or international operating agencies and from pooling their air services on any routes or in any regions. but such organisations or agencies and such pooled services shall be subject to all the provisions of this Convention, including those relating to the registration of agreements with the Council. The Council shall determine in what manner the provisions of this Convention relating to nationality of aircraft shall apply to aircraft operated by international operating agencies.

Article 79 : Participation in operating organisations

A State may participate in joint operating organisations or in poling arrangements, either through its government or through an airline company or companies designated by its government. The companies may, at the sole discretion of the State concerned, be state-owned or partly state owned or privately owned.

CHAPTER XVIII DISPUTES AND DEFAULT

Article 84 : Settlement of disputes

If any disagreement between two or more contracting States relating to the interpretation or application of this Convention and its Annexes cannot he settled by negotiation, it shall, on the application of any State concerned in the disagreement. be decided by the Council. No member of the Council shall vote in the consideration by the Council of any dispute to which it is a party. Any contracting State may, subject to Article 85, appeal from the decision of the Council to an ad hoc arbitral tribunal agreed upon with the other parties to the dispute or to the Permanent Court of International Justice. Any such appeal shall be notified to the Council within sixty days of receipt of notification of the decision of the Council.

Arbitration procedure

If any contracting State party to a dispute in which the decision of the Council is under appeal has not accepted the Statute of the Permanent

CHAPTER XIX WAR

Article 89 : War and emergency conditions

In case of war, the provisions of this Convention shall not affect the freedom of action of any of the contracting States affected, whether as belligerents or as neutral. The same principle shall apply in the case of any contracting State which declares a state of national emergency and notifies the fact to the Council.

Article 93 : Admission of other States

States other than those provided for in Articles 91 and 92 (a) may, subject to approval by any general international organisation set up by the nations of the world to preserve peace, be admitted to participation in this Convention by means of a four-fifths vote of the Assembly and on such conditions as the Assembly may prescribe: provided that In each case the assent of any State invaded or attacked during the present war by the State seeking admission shall be necessary.

Article 93 bis

(a) Notwithstanding the provisions of Articles 91, 92 and 93 above:

(1) A State whose government the General Assembly of the United Nations has recommended be debarred from membership in international agencies established by or brought into relationship with the United Nations shall automatically cease to be a member of the International Civil Aviation Organisation;

(2) A State which has been expelled from membership in the United Nations shall automatically cease to be a

member of the International Civil Aviation Organisation unless the General Assembly of the United Nations attaches to its act of expulsion a recommendation to the contrary.

(b) A State which ceases to be a member of the International Civil Aviation Organisation as a result of the provisions of paragraph (a) above may, after approval by the General Assembly of the United Nations. be re-admitted to the International Civil Aviation Organisation upon application and upon approval by a majority of the Council.

(c) Members of the Organisation Which are suspended from the exercise of the rights and privileges of membership in the United Nations shall upon the request of the latter, be suspended from the rights and privileges of membership in this Organisation.

Article 94 : Amendment of Convention

(a) Any proposed amendment to this Convention must be approved by a two-thirds vote of the Assembly and shall then come into force in respect of States which have ratified such amendment when ratified by the number of contracting States specified by the Assembly. The number so specified shall not be less than two-thirds of the total number of contracting States.

(b) If in its opinion the amendment is of such a nature as to justify this course, the Assembly in its resolution recommending adoption may provide that any State which has not ratified within a specified period after the amendment has come into force shall thereupon cease to be a member of the Organisation and a party to the Convention

COMMUNICATIONS COMMAND AND CONTROL

The crowded spectrum

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ABSTRACT

Two key issues arise when the crew are removed from the aircraft. The first is how to get data to and from the aircraft (communications); and the second is how to operate the aircraft effectively (Command and Control). All the various methods used rely on the electromagnetic spectrum and useable space in this spectrum is becoming increasingly scarce. The provision and protection of this resource for the aviation community is an important issue. For UAV systems it could be the difference between success and failure.

Whilst the number of UAVs remains small the problem may be contained. However if the UAV industry is to experience the growth it expects, this may well be the most limiting factor.

1 INTRODUCTION

1.1 UAV communications

Communications plays a much more important part in the overall operation of a UAV than it does for manned aircraft because the men-in-the-loop are on the ground. All operations with a UAV must be made with due regard to the fact that all the decision making processes occur on the ground, either before the flight or during the flight operation.

The prime aim of most flights is to ensure that the payload is positioned in the right place to do its job. Therefore the whole mission revolves around the payloads and not around the aircraft. This is a fundamental departure from the majority of the manned world where more then 95% of flights are concerned with moving people and freight. Despite what might be thought, most military flights do the same.

The big issue for communications is what frequencies to use and how much data there is to be transmitted. Useable frequencies are in short supply worldwide and so design of the UAV must take into account where the major processing of data is carried out as this leads to design criteria for where communications takes place and how much needs to take place. The American Global Hawk UAV has on board a very powerful computer to process its data to cut down the amount of data that needs to be transmitted.

1.2 Current aircraft systems

Today's manned aircraft are equipped with a bewildering array of systems for communications purposes including:

- Landing Aids
- En-route navigation
- Dependent Surveillance
- Air/Ground ATC Communications

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.

- Operations control
- Collision Avoidance
- Passenger Telephones

These systems work in a variety of frequency bands that are subject to increasing depletion through an ever increasing demand on spectrum by other industries outside the aviation industry. For the UAV industry to emerge into the 21st century it must address these issues.

2 COMMUNICATIONS INSTITUTIONAL FRAMEWORK

2.1 International Telecommunications Union (ITU)

The forerunner of the present ITU was originally established in 1863 to be the international organisation dealing with line communications, and was later extended to cover also radio communications. The organisation was renamed to become the ITU in 1932. In 1947 it was accorded Specialised Agency status by the UN (for Telecommunications), some months after ICAO was similarly treated (for civil aviation). Membership of both organisations is similar and in excess of 180 signatory governments. Its primary members come from the Telecommunications Administrations, or the Radiocommunications Agency of its Members States.

The organisation has three quite distinct sectors of interest - Radio communications, Telecommunications Standardisation (mostly line communications standards), and Telecommunications Development. The General Secretariat in Geneva provides the technical support and administration. The executive body of ITU is the Administrative Council, with a representative membership of some 15 countries, which meets yearly for two weeks and approves, inter alia, the Agenda of the next two yearly WRC as well as defining policy issues referred to it by Conferences, etc.

Nowadays however there is a second and lower tier of membership from commercial and industrial sources, laboratories, etc., with reduced rights and privileges. There are around 150 of these, who have the choice of subscribing to any one, or all, of the three ITU sectors. In institutional terms, the incorporation of this large commercial segment has the potential to have a significant influence on events and this is becoming more evident as pressures on the spectrum grow.

The World Radio Conferences (WRC) are held at two yearly intervals, the items discussed at World Radio Conferences (WRC) concern the Radio Regulations which contains the Table of Frequency Allocations to the individual services, such as the aeronautical services. Whilst ICAO and Eurocontrol attend as Observers, they are not permitted to make Proposals, or to vote, and this can be a very severe constraint on the capability to influence events. Furthermore, in regard to discussing aeronautical matters, the ITU does not consider it is barred from discussing and agreeing technical aspects affecting aviation, provided only that the discussion contains a sufficient number of delegates professing to be aviation experts.

The record of aviation support to ITU-R meetings is very poor with rarely more than 3 or 4 delegates, having to present and defend vital subjects against very well organised opposing interests. ITU makes no distinction between experts from aviation authorities and others claiming similar expertise, who are often operating with a brief from, and occasionally employed by, the competing interest. Good organisation and briefing for these meetings is of prime importance in securing objectives.

2.2 European Conference of Postal and Telecommunications Administrations

The European Conference of Postal and Telecommunications Administrations (CEPT) was set up in 1959 and has 43 members drawn from EU, EFTA and adjacent States. Its objectives are to improve the co-ordination between members. CEPT is a voluntary body but operates as the quasi-official voice in the matters in which it specialises. Its relations with the EC are defined in a Memorandum of Understanding.

CEPT has three main committees - Postal , General Telecomms, and Radiocommunications. The European Radiocommunications Committee (ERC) with its permanent support in the European Radiocommunications Office (ERO) based in Copenhagen, acts as the machinery to maintain the co-ordination. The CEPT through the ERO is very active on radio regulatory matters and the preparations for WRC.

The ERC produces Decisions, and Recommendations, the former dealing with more significant matters than the latter. A consultation process for Decisions after which they become agreements within CEPT is a standard feature. The ERO is the centre of expertise and carries out studies, many funded from EC resources and many dealing with spectrum matters.

The CEPT is essentially composed of telecommunications interests, and mobile communications matters receive considerable attention. Their spectrum work however touches all other radio interests (broadcast, maritime, defence, etc.), but their expertise in these, as with aviation, is noticeably less. A view within CEPT which has prevailed for some time is that aviation in the past were treated too liberally and as a consequence is holding spectrum which it will never utilise. The view has not been helped by the failure of aviation to use the satellite, and the MLS spectrum.

Aviation has traditionally operated within its own envelope of a strong co-operation throughout the globe with ICAO SARPs and airborne MPS being developed in isolation within a well understood framework. Partly as a consequence of this the role of radio in air operations is not well understood by others. A primary problem is to place the safety element in perspective, to articulate it in meaningful terms, and wherever possible to illustrate it with data and information from real life, stressing to an appropriate degree the consequences when things go wrong. Any action which will increase the appreciation and lead to a higher degree of sensitivity in these organisations can assist in the task of retaining needed allocations.

2.3 European Telecommunications Standards Institute

The European Telecommunications Standards Institute (ETSI) is the European standards body for telecommunications, and works very closely with the other standards bodies in Europe. Their standards are voluntary only, but these 3 bodies are franchised to carry out standards work for the European Union.

In this process the voluntary European Standard is converted to become a Technical Basis for Regulation (TBR) and circulated amongst its 28 National Standards Members for agreement to conversion to become a European Telecommunications Standard. In 1997 ETSI had published over 50 standards, with a further 100 standards in the mobile field under discussion.

The membership of ETSI is very wide, including not only radio administrations but many industrial companies, research laboratories, manufacturers, national standards organisation, network and service providers, and many others.

2.4 Ad Hoc Aeronautical Spectrum Protection Group

Communications systems provide the basis for the safe and efficient support of operations for air navigation and Air Traffic Management services. In recent years, all of the spare capacity in the usable radio frequency spectrum - from about 9 kHz to 60 GHz - has been depleted. New services can now only be accommodated either by the removal of existing allocations or by an acceptance of frequency sharing between two compatible services. In this situation aviation has no special privileges and must defend and compete for its requirements in the same way as any other user. The radio spectrum is also taking on a more commercial and economic dimension with the advent of buying and selling spectrum, "spectrum pricing".

Because of this it has been agreed within the ECAC and by the Eurocontrol Committee of Management that a framework should be created to defend the civil aviation interests in the radio frequency spectrum by obtaining favourable decisions in :

- International radio band allocation: to provide sufficient capacity for the operation and deployment of existing systems and for the development of future systems ,
- Safety and Quality: to ensure that emissions from non-aeronautical systems do not cause harmful interference to, or degrade the quality of, aeronautical systems.

The exclusive world wide frequency allocations to terrestrial aeronautical services in the ITU Radio Regulations, with the exception of HF frequencies, are controlled and co-ordinated by aviation itself as a special recognition by radio regulators that it is a safety service. As a further element in this recognition the system specifications (except for Electromagnetic Magnetic Compatibility requirements) for international communications and navigation are developed and agreed on a world wide basis within ICAO, RTCA (Radio Technical Communications Agency), and EUROCAE (European Organisation for Civil Aviation Equipment). This is considered by many radio regulators to be a sensible, although not an automatic, delegation of powers.

Space systems, due to their multi-purpose and multi-national involvement, can not be treated in an identical manner. Here the target for aviation is to ensure that the frequency provision is adequate in capacity terms for ongoing, and long term expansion needs, and that its quality is appropriate to the needs of a safety service with high integrity requirements. In this change of emphasis the co-ordination processes of regional, and world wide bodies, becomes even more important, to firstly define global policies, and secondly to identify regional variations or supplements.

3 COMMUNICATIONS ISSUES

3.1 Types of Communication

There are a number of ways that current manned aircraft communicate and a number of reasons why they communicate or receive signals. Aircraft surveillance, navigation and data communications are all functions that require some form of communications as the following list covers some examples:

Surveillance/Collission avoidance

- Secondary Surveillance Radar (SSR) Mode A&C
- Automate Dependent surveillance (ADS)
- Tactical Collision Avoidance System (TCAS)

Navigation

- Satellite Navigation (Satnav)
- Instrument Landing System (ILS)
- Distance Measuring Equipment (DME)
- VHF Omni directional Range (VOR)

Data Communications

- Satellite Datalink
- VHF Datalink
- Mode S Datalink

Voice Communications

- Radio (HF, VHF & UHF)
- Satellite Communications (Satcomms)

Some of these are explained further in Appendix A and B. The primary means of command and control from an ATM perspective is still by voice communications. All voice communication between

aircraft and ground stations are accomplished using the English language and by use of standard phraseology which is laid down by ICAO. The exception is that the local language may be used where all stations on a single frequency are fluent in that language. The phraseology has been developed over a number of years such that ATC instructions and advice are clear concise and unambiguous. The information commonly conveyed by voice communications between ground and air comprises:

- ATC clearances
- ATC instructions
- Meteorological information
- Aeronautical Information (e.g. relevant airfield data)
- Traffic information

From an ATM perspective there is also a ground/ground perspective concerning communication requirements between ATC centres. Translated into a UAV scenario there will be need for communications between ATC centres and UAV Control centres.

Apart from Voice Communications UAV systems can be made to utilise most of these in some way or other although some will be more useful than others.

3.2 UAV considerations

From an ATC perspective a UAV is no different from any other aircraft. The vehicle must still be controllable by others outside of the ATC arena and the UAV should communicate with ATC and follow all instructions given.

Currently VHF radio links are normally used for communication and HF radio or satellite links for oceanic control. Since communication between ATC and aircraft is currently procedural and all voice based, the UAV is not easily accommodated at present in the ATM environment. The UAV scenario will require that other aspects be considered such as:

- Safety critical control links
- Communication security
- Reduction of communication load
- Telemetry for aircraft status
- Payload data

With these additional considerations, it is easy to envisage a negative impact on an already crowded and heavily used frequency spectrum. It is unlikely that any part of the spectrum will be any less crowded than others and it is likely that manned aviation will take precedence over unmanned aviation.

Perhaps the key issue is control of the UAV. Whether command and control of the UAV can be adequately addressed in the current ATM framework.

3.3 Air/Ground/Air Communications

The big issue in this area is the shortage of VHF and UHF frequency bands. A system already operates around the world where the same frequency is used more than once, each within a Designated Operating Coverage(DOC). There is still interference from other close frequencies and often the two DOC areas can conflict.

Along with the frequency shortage is the bandwidth limitations so that VHF datalinks are limited to short messages. The transition to digital communications systems will improve this situation, however there is another factor which occurs, that of time delays. This is caused by the air and ground based processing systems especially in multiplexed situations.

3.4 Ground/GroundCommunications

The ground scenario is interesting from the point of view of UAV Control Centres communicating with conventional ATC centres. The newer UAV system may be more capable than their older counterparts and the system performance differences may be an issue. The standards that the UAV control centre will be built to and the availability of suitable links to the ATC centre may cause problems.

As the ATC centres are improved there is increasingly greater reliance on computer processing of data and computer-computer data exchange will become an increasingly important issue.

CONCLUSION

There are a significant number of threats to current and future communications systems as mentioned above and the following list is not exhaustive:

- Frequency management failures (Regulatory/Allocation)
- System failures (equipment based)
- Security/Safety failures
- External interference
- Sideband interference
- Simultaneous transmissions
- Malicious/Hoax transmissions

This brief view of communications from the existing manned aviation view highlights the many issues. Communications is already a fundamental part of the manned aviation world and the spectrum available even for current operations is severely limited. With the advent of the UAV system and its reliance on good communications both for the payload and the aircraft system, there is a need to ensure that safety and effectiveness are not compromised.

The fact that the majority of air transport is carried out in civilian airspace under civilian rules, means that communications, command and control has got to be made effective in peacetime. For this to occur the UAV aviation community must recognise the current institutional framework and its processes and influence them to its benefit. If not then the UAV industry will not progress far and UAV systems will be relegated to a small niche and heavily regulated market place. Even the military will suffer as they will not be able to guarantee the integrity and operational effectiveness of their systems.

APPENDIX A

NAVIGATION SYSTEMS

VHF Omni-Directional Radio Range (VOR)

This is a VHF transmitter which radiates in a form which enables precise directions from the beacon to be derived by an aircraft based receiver. These directions are called radials and very accurate navigation along radials is possible. The VOR has been the standard airways navigational aid for many years. Reception is limited to comparatively short ranges (usually less than 100 miles). There is a Morse code identification voice recordings superimposed on the VOR carrier signal.

Distance Measuring equipment (DME)

This is a UHF responding beacon on the ground. They are usually associated with a VOR. An aircraft requiring distance information from a particular DME transmits a coded signal on a discrete frequency which is received by the DME beacon and retransmitted to the aircraft. The DME receiver on the aircraft derives slant range by measuring the time taken for the signal to travel between aircraft and beacon. DME measurements are very accurate, typically to within 0.1 mile.

Tactical Aid to Navigation TACAN

This is primarily a military aid that combines the features of the VOR and DME (operating in the UHF band). Bearing and distance measurements are provided simultaneously by the beacon. Civil aircraft can make use of the DME element of a TACAN facility.

Instrument landing System (ILS)

This is a ground based landing aid which comprises two elements. The localiser is a VHF transmitter which indicates the extended runway centre line in the horizontal plane. The aircraft receiver gives the pilot an indication of being left or right of the desired approach path and whether to turn left or right to regain the centre line. The glide slope indicates the approach path in the vertical plane and is set tot he required approach angle (usually three degrees). The pilot is informed of his position relative to the required path and whether to reduce or increase his rate of descent. ILS is currently the standard civil approach aid. In some instances it can provide capability to land in very limited or even zero visibility.

Microwave Landing System (MLS)

This is the future replacement for ILS which is now in limited service. Its method of operation is similar to ILS in that two beams are provided for guidance in the horizontal and vertical planes. However, the nature of microwaves produces greater accuracy and a wider area of service. Thus it provides the capability to use more than one approach path or for paths which are not straight lines.

Inertial navigation System (INS)

This is a self contained system within an aircraft which navigates by very accurate dead-reckoning. Accelerometers measure aircraft movement in all directions and input is taken from other aircraft sensors (for example altimeter). Accuracies in the order of 1 mile drift per hour can be achieved and even these can be eliminated when cross checking with other navaids is carried out periodically. However, system accuracy depends on correct input of the originating co-ordinates of the flight and failure to do so may lead to gross navigational errors.

Global Positioning System (GPS)

This is a satellite-based navigation system. Messages (both encrypted and unencrypted) are transmitted from a series of satellites in earth orbit. By comparing time of arrival differences with the messages and the satellite positions the aircraft position can be calculated. Accuracies of the order of a few metres can be obtained from the encrypted codes. GPS is however not certified for sole means navigation and is purportedly easy to jam. Despite this it is becoming heavily utilised by a number of different industries such as road hauliers.

APPENDIX B

SURVEILLANCE SYSTEMS

Secondary Surveillance Radar (SSR)

SSR operates by the radar broadcasting out a signal which is received by aircraft equipped with transponders. The aircraft then transmit data which allows the ATC to obtain its position, is identity (Mode A), and its height (Mode C). Mode S radars and suitable equipped aircraft can also send data.

Automated Dependent Surveillance (ADS)

Most of the globe is not covered by radar. Using ADS, however, an Air Traffic Control Centre (ATCC) can see the current position of an aircraft almost anywhere in the world. A controller can also examine the aircraft's intended flight path and other information held in their onboard navigation systems. This data can be downloaded even in airspace not covered by radar, such as the oceans or sparsely populated areas.

An aircraft reports its position via an orbiting satellite. The message is routed to the current ATCC for that aircraft. If the ATCC needs to send instructions to the pilot, it can do this using other datalink systems to send data messages, or satellite voice services to speak to the crew directly.

There are already aircraft trialling the system and the concept will revolutionise the management of aircraft in remote regions.

Tactical Collision Avoidance System (TCAS)

Aircraft that are TCAS equipped emit a signal (Mode S) which is received by participating aircraft and advisory de-confliction messages are provided to the pilot. This allows the pilot to take avoiding action when necessary. The difficulty faced however is that aircraft that are not equipped are not seen.

Tools for Optimization and Validation of System Architecture and Software

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DGA/DSA/SPMT – Architecture des Systèmes de Drones
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75015 Paris

Abstract : UAV systems architectures rank among the most complex ones with high safety requirements. Some new software tools have recently emerged that are worth to be known. This lecture was given to advertise four of them on the following topics : 1) Static verification of real time software, to avoid run-time errors, typically what happen for Ariane V ; 2) Simulation of real time architecture to optimize conception and validate the final choice ; 3) edition of command and control software with interpreted properties like on-line automatic reprogramming ; 4) optimization under constraints for continuous and discrete processes.

I - Static verification of real time software

*The software product that is described is developed and maintained by **PolySpace Technologies**, start-up from INRIA, research institute where the research was conducted. The point of contact is Daniel Pilaud, PolySpace T., 655 av. de l'Europe, 38330 Monbonnot-St-Martin, France ; phone / fax : 00-33-476-61-52-60 / 54-09.*

The purpose of the software is to detect run time errors (RTE), compliance with temporal constraints (dead-lock, live-lock), compliance with observable outputs, as well as non-deterministic constructs in real time software. Its technology is based on **INRIA** researches dating back to 1985 on static verification by abstract interpretation. It has been industrialized by PolySpace and experimented convincingly on industrial basis : ARIANE V, Atmospheric Reentry Demonstrator, satellites, railway transport, automotive…

An example of run-time error is the division by zero that can be hidden in a procedure as follows :

```
Procedure foo (
        RR : in Float_64 : F1 : in Float_64 ;
        F2 : in Float_64 : F3 : in out Float_64) is
tmp : Float_64 ;
begin
if (RR /= 0.0) then
        F2 := F1 / RR ;
```
here, RR may be very small but is not 0.
```
        …
        tmp := RR**2 ;
        F3 := F1 / tmp ;
```
here, tmp may be equal to 0, or F3 may be huge.
```
end if ;
end foo ;
```
The problem occurs when tmp < 2^{-511} and F1 > 2^{511}.

The purpose is to detect and identify the error type, localize it precisely in the source code and depict the error context. In that case, the sofware will issue :
" possible error of correctness condition : denominator must be non zero
computed range : {0 <= [expr] <= 10**10}
in task1.prc_val at "validate.adb" line 24, column 18 : F3 := F1 / tmp ;"

Having in mind that 30 to 40 % of remaining errors are RTE, it is worth while using a tool that automatically detects :

- concurrent access on shared data,
- non initialized variables,
- unreachable code,
- out-of-bound array accesses & buffer overflows,
- arithmetic overflows & underflows (integer, floating point),
- arithmetic exceptions : division by 0, square root (<0),…

The software makes an exhaustive and unambiguous RTE identification through 4 classes of correctness :

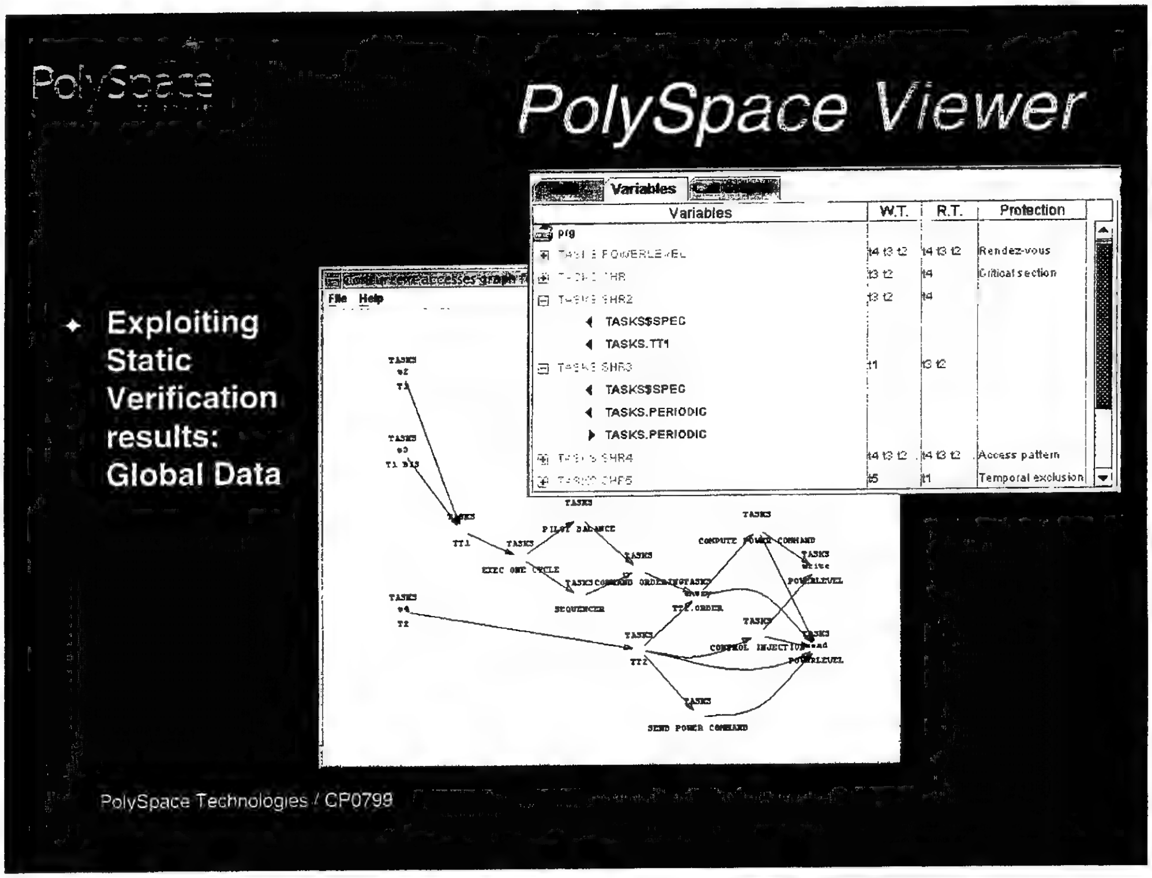
- "**certain error**" that are pinpointed by a red color,
- "**potential error**" in orange, that have to be inspected,
- "**always correct**" in green, for which the correctness is proven,
- "**non executable**" in black for unreachable code sections.

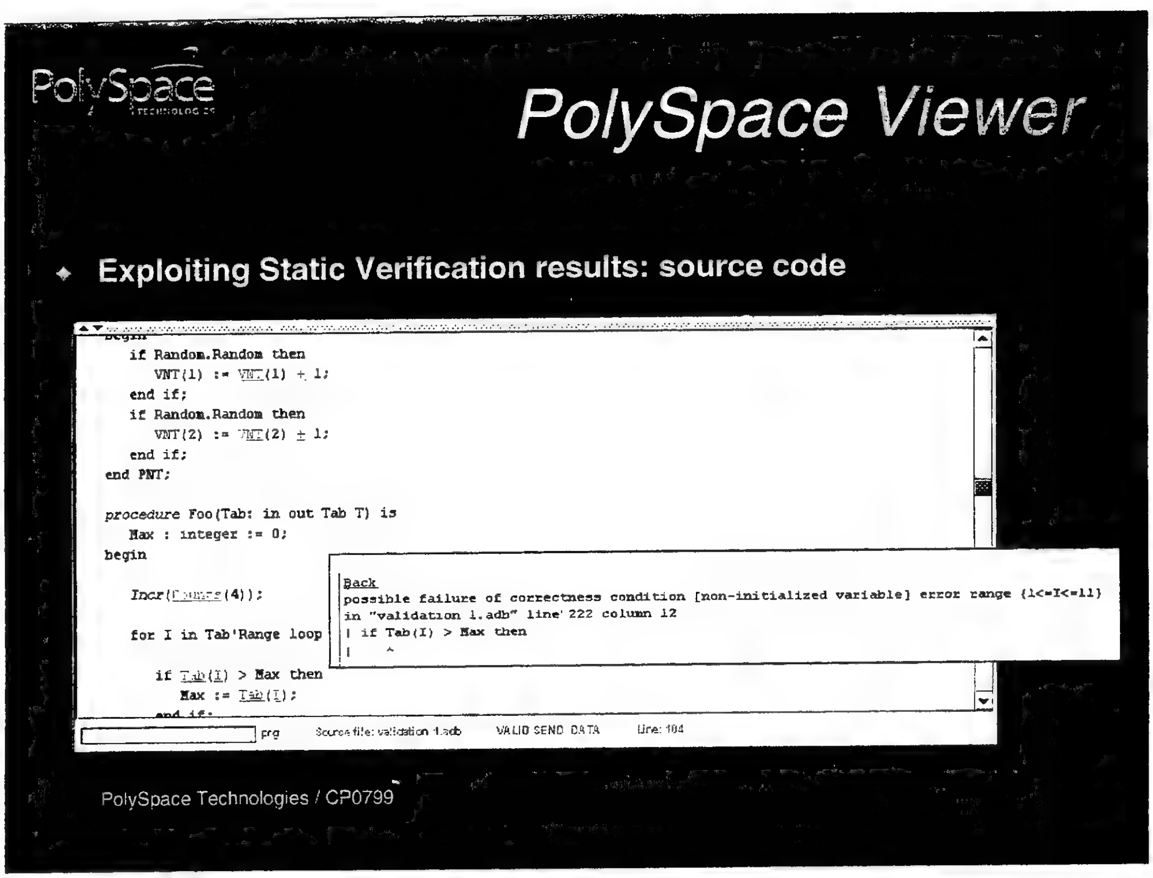
An operation causing an error is **necessarily** classified as a potential or certain error.

The principle of the checking is based on polyhedron analysis of always a super-set of the exact solution. The efficiency of the selectivity rate is increased by splitting the state space by several polyhedrons, the use of integer lattices, …

The selectivity rate is important also to save man power. For example, the safety requirements for nuclear power plant induces to have two software specialists to verify the code written by a third one, the ratio is less severe in aeronautical industry but still one might need one verifier for each programmer. If the tool is capable to automatically classify "green" or "red" 85 % of the code,

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.


PolySpace
PolySpace Viewer
Exploiting Static Verification results: Global Data
Variables
Variables
W.T.
R.T.
Protection
prg
TASKS$SPEC
TASKS.TT1
TASKS$SPEC
TASKS.PERIODIC
TASKS.PERIODIC
Rendez-vous
Critical section
Access pattern
Temporal exclusion
File Help
SEND POWER COMMAND
PolySpace Technologies / CP0799


PolySpace
PolySpace Viewer
Exploiting Static Verification results: source code
if Random.Random then
VNT(1) := VNT(1) + 1;
end if;
if Random.Random then
VNT(2) := VNT(2) + 1;
end if;
end PNT;
procedure Foo(Tab: in out Tab T) is
Max : integer := 0;
begin
for I in Tab'Range loop
if Tab(I) > Max then
Max := Tab(I);
Back
possible failure of correctness condition [non-initialized variable] error range (1<=I<=11)
in "validation 1.adb" line 222 column 12
| if Tab(I) > Max then
prg
VALID SEND DATA
Line: 104
PolySpace Technologies / CP0799

that is if the potential errors are reduced to 15 % of the code, then the final inspection needs much less time.

The tool was currently experimented on software of 60 to 100 thousands lines of code. For example, after the crash of Ariane V, it was decided to use this tool to scrutinize the different codes used on the rocket. Ariane V technicians had identified the source of the crash and wanted to prove that this tool was capable to detect the origin of the error in order to apply it to the future generations of codes implied in navigation and guidance pilots. During Ariane experiment, the software tool was thoroughly tested for :

- control and data flow analysis: call graphs, identifying global data, checking initialization,
- interference analysis: finding potential shared memory interference between conflict tasks using the Bernstein criterion,
- scalar range analysis : inferring and checking range conditions for all discrete variables,
- floating-point domain analysis: computing and approximate domain for each floating-point variable, checking the validity of operations.

The second industrial experiment was brought on the Atmospheric Reentry Demonstrator to analyze its critical software (navigation and guidance pilots) including three interacting parallel tasks and 26 thousands lines of code.

To summarize the highlights of this recent tool, the following characteristics can be listed :

- classifies with a very high selectivity rate (between 80 and 95 %),
- works on the following program conditioning : ADA 83 or C ANSI, encapsulation of non-standard constructs,
- the user can tune the duration of the processing from 2 hours, or a day to a week-end,
- the "red tape" consisting of listing all the potential errors is automatically done by the tool.

The time devoted to verification is divided by 5 or 6 and no error or potential one is missed.

II - Optimization of real-time architecture and validation

The second tool presented here has been designed and developed by Michel BARAT from ONERA – research center specialized in Aeronautics and Space Technologies, 27, avenue de la division Leclerc, 92 322 Châtillon cedex, France ; phone / fax : 00 33 146 73 43 88 / 41 41.

The software is a simulator called "SAHARA" that stands for Heterogeneous Architecture Simulator for Agents and Active Resources. SAHARA is a simulator of discrete event process that was originally created for the architecture design of the "pilot associate", Dassault Aviation Program.

SAHARA, initially meant for design, is now moving towards new applications, involving validation and potentially airworthiness certification.

If one examines the tools existing in architecture design, one will come to the conclusion that there is nothing to create and optimize a multiple agent architecture. The only field where solutions are emerging is the area of image processing computers. Solutions are possible in this domain because the structure of the computing is very homogeneous. When agents are heterogeneous, the only way to optimize the design of an architecture is to simulate the process allowing to achieve a solution through an iterative procedure.

One of the main advantages of SAHARA is to be capable of simulating a system during design when components are not well defined or incomplete. The simulator answers this issue by offering a three layer process description : functional, structural, and component level. The three levels of description are the following :

- the functional level can be used to analyze control command of systems with no time delay that is when the available time between two events is always long enough to fulfill the requirements. This stage brings validation of the functional description according to specifications of the system.
- The structural level gives a result if you consider infinite resources. At this stage, you can optimize the options of organization according to goals and constraints.
- The third level describes the precise logical-material system and allows to take into account the impact of time on system behavior. For example, the availability delay of data on data links.

The simulator tests the system according to environment stimulus that can be described with statistical options.

The SAHARA simulator is based on an interpreted Petri net modeling that can take into account asynchronous event, predictable or unpredictable and stochastic events. The elementary level of SAHARA can also be seen as a production rule : If (Condition) Then (action).

The data are described according to their interaction and the way they are exchanged. For instance, a sensor brings out an image but what is of interest on the simulation point of view is not the pixels but

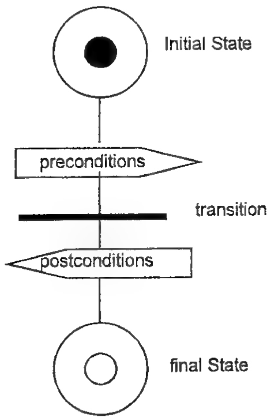
◊ the image size for its impact on communication delay,
◊ and the image pitch for its impact on computation effort.

The system is described using "black boxes" defined by their :

- inputs,
- outputs,
- context,

SAHARA Model

Rule : If condition Then action or Interpreted Petri Net



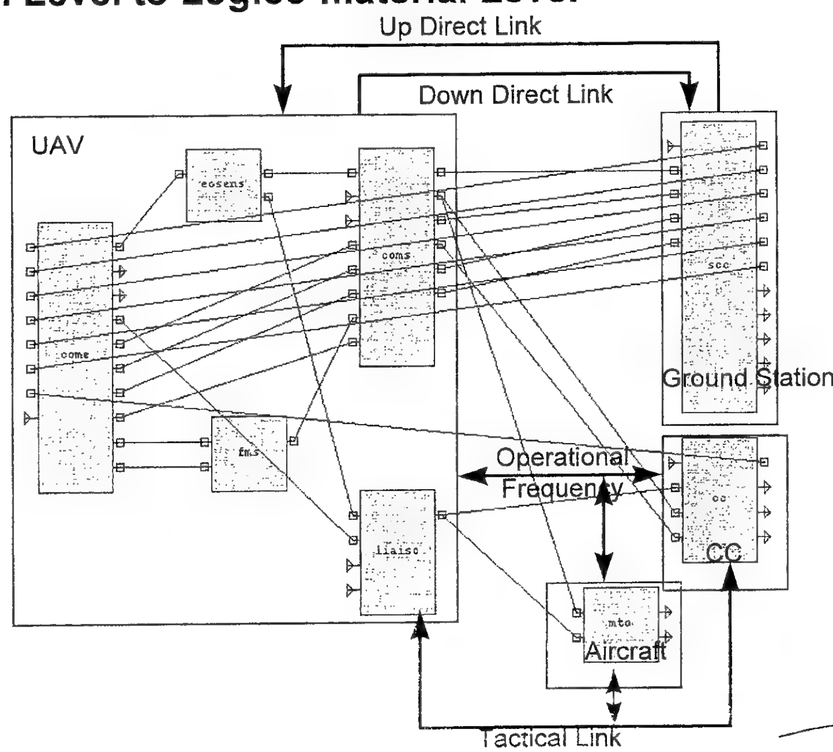
event = data + message

Model : asynchronous
predictable
unpredictable
stochastic

equivalent models
Automatons
Petri Net

ONERA

Structural Level to Logico-material Level



ONERA

- and transformation. The transformation is the propagation of data through the function according to inputs and context.

An example of behavior definition is given below. A behavior can be either deterministic or random.

```
(def_function threadreact
(inputs thread)
(outputs reaction)
(body
 (trigger (thread (equal $thread.level 'urgency))
            (100 immediateReact (thread)
        ((reaction ((type reflexe))))) )
 (trigger (thread (equal $thread.level 'basic))
            (50 destructionThread (thread)
((reaction ((type destruction)))))
            (50 avoidanceThread (thread)
((reaction ((type avoidance)))))) ))
```

What is specified here is :

- for a threat of urgent level : the function applies a determinist behavior and propagates the reaction,
- for a threat of basic level : the function applies a stochastic behavior :
    - in 50% of the cases, the behavior of destroying the threat,
    - in 50% of the cases, the behavior of avoiding it.

One can also depict a periodic behavior like the one that follows :

```
(def_function EOsensor
   (inputs EOcdt)
   (outputs EOframe TacticalFrame)
   (body
        (trigger (EOcdt (frequency (periode 2))
                          (begin (EOcdt (equal
$EOcdt.state 'on)))
                          (end (EOcdt (equal
$EOcdt.state 'off))) ))
                    (100 EOFrameProduct ()
(EOframe ((length 980 ))))) ) ))
```

In this example, the Electro-Optical sensor produces every 2 units of time an image waiting 980 kbytes.

Delay and synchronized signals can also be taken into account as follows :

```
(def_function evaluationReact
   (inputs thread reaction)
   (outputs reactionNotification defaultNotification)
        (body
            (trigger reaction (maxDelay 10)
                    (begin (thread (equal $
thread.state 'on)))
                    (end (thread (equal $
thread.state 'off)))
                          (outOfDelay (100
abnormalReact () ((defaultNotification)))) ))
                        (100 normalReact ()
((reactionNotification)))) ))
```

In this example for asynchronous signal, it is specified that the 2 signals – threat and reaction must be available within a time laps of 10 units. If the time constraint is satisfied, the "notification" of reaction is propagated. If not, the "default" of reaction is propagated.

The user chooses the unit of time according to his need in terms of central processing units, data links, resources. Among resources the user can depict a human operator.

The different applications of SAHARA have given birth to special functions simplifying the user's life :

- interruptible,
- any time function (interruptible, contractual, consultable, latency delay, quality level, context evolution).
- command supervision action.

At function level, one specifies :

- the length of computation through an instruction code measurement,
- the size of the dynamic memory necessary,
- for data exchange, the receiver of the data and the size of the information produced. This size is used to compute the propagation delay via the data link.

At structural level, one looks for the best system composition. For instance, so far as the memories are concerned, they can be defined as :

- local,
- shared,
- reactived,
- buffer (FIFO),…

At this level the simulator can compute the behavior of the system with theoretical resources of infinite capacity.

At hardware level, the logical architecture becomes real with actual resources : CPUs, memories, data links, human agents. The communication channel can be managed according to different strategies :

- either point to point
    - first arrived first served,
    - prioritized ,
    - …
- or broadcast.

SAHARA has a graphic viewer that gives life to the boxes and links during the simulation for a better understanding of what's going on.

The simulator allows to evaluate :

- for each CPU resources :
    - its instantaneous workload,
    - its maximum load,

    - its average load,

- for each data link :
    - the maximum delay of data propagation,
    - its average propagation delay,

- for each memory :
    - its potential conflict,
    - its potential overflow,
    - …

With all this information, the designer can reshape the architecture of his system and through an iterative process can optimize it.

Today's simulator is based on :
- Work Station Sparc SUN 4 5.6,
- W/WINDOWS,
- Le_lisp and Aida (Ilog)
- MERING 2, Actor and Object library.

The simulator served the following programs :
- in 1989 : to model and simulate the electronic copilot of Dassault Aviation,
- in 1992 : to model and evaluate the UGV "DARDS" architecture for Dassault Electronique, the architecture of this UGV was so safe that never a failure occurred during 7 years of experimentation and demos,
- in 1995 : to accomplish a feasibility study in the context of underwater warfare,
- Nowadays, it is currently used for MAE (Medium Attitude and Long Endurance) UAV architecture design and validation, with the contribution of Sagem and Aérospatiale Matra.

The nest step is to specify improvements of SAHARA in order to enable it to become a useful tool in the process of airworthiness certification of UAVs.

III - Edition of command and control software

The software presented now is called PROCOSA, acronym for the French title "Programmation et Conduite de Systèmes Autonomes" witch can be translated into "Programming and execution monitoring of autonomous systems". This software tool was made-up by Claude BAROUIL from ONERA Toulouse, 2 avenue Edouard Belin, B.P. 4025, 31055 Toulouse Cedex 4, France; phone / fax 00 33 5 62 25 25 61 / 64.

This part is laid out from a paper issued by the author of PROCOSA called "Advanced Real time Mission Management for an AUV" edited in September 1999 for the NATO RESTRICTED symposium on advanced mission management and system integration technologies for improved tactical operations.

The idea behind this tool is to allow automatic reprogramming of autonomous uninhabited vehicles. The code that is automatically issued fulfills the safety requirements and is validated.

An autonomous system is characterized by a high number of functions which are difficult to modify through hardware. All the components at low level are complex and costly to develop. PROCOSA allows to define vehicle behaviors as the organization of control flow and data flow between functions and defines a mission in terms of cooperation between behaviors. Once these functions are set, it is easy to construct a decision level layer.

PROCOSA proceeds into programming a mission by a hierarchical and procedural method : a plan is a partially ordered set of macro actions. A macro action is a particular behavior which can be considered as a sub-mission and is described as such. So, the first step consists in developing those general purpose macro-actions : perception, localization, motion control, payloads…

PROCOSA edits mission plan changes without recompilation : a mission plan refers to behaviors which themselves refer to behaviors and to functions. Changes in mission plans concern only the way behaviors are requested. Functions are never modified during a mission execution. When no function has to be modified, changing a behavior specification is feasible by the mission UAV operator – and not by a system specialist.

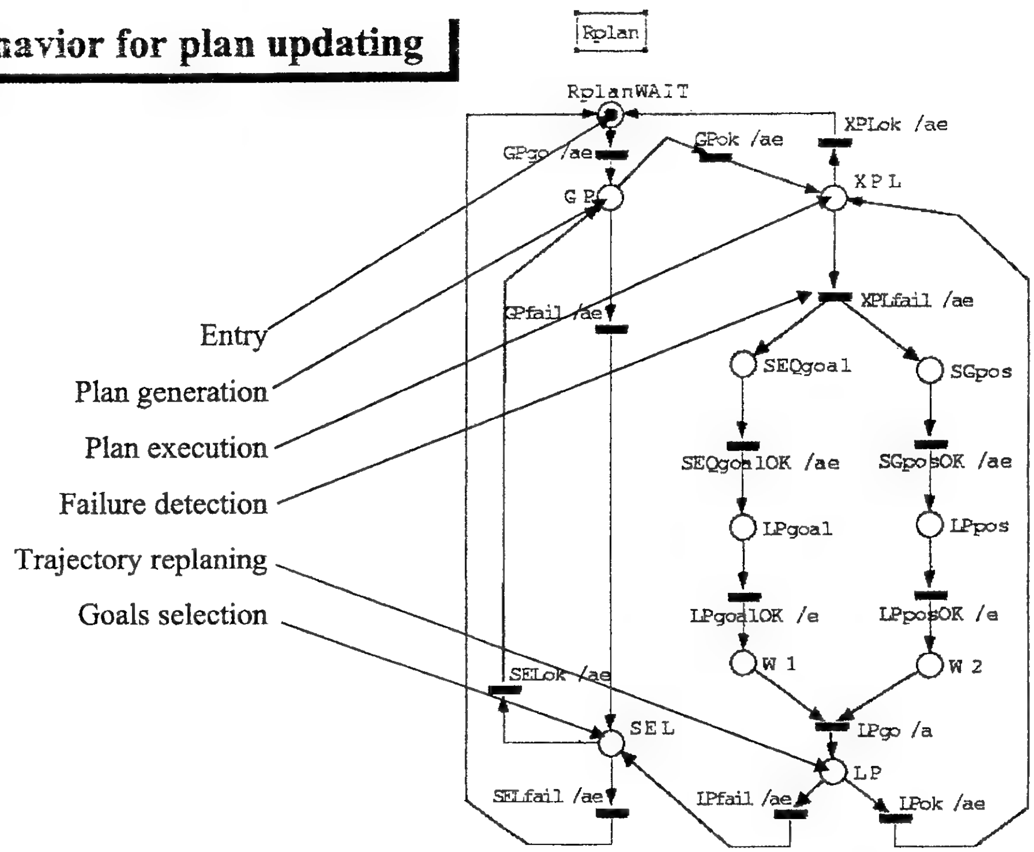
The hierarchical representation simplifies the mission plan design as well as its graphic representation. PROCOSA offers a graphic-based mission plan language, so that a human operator can easily express mission specifications. During mission execution, and when there exists a communication link from the UAV to the operator interface, the same language allows the current mission state to be displayed on the graphic mission representation.

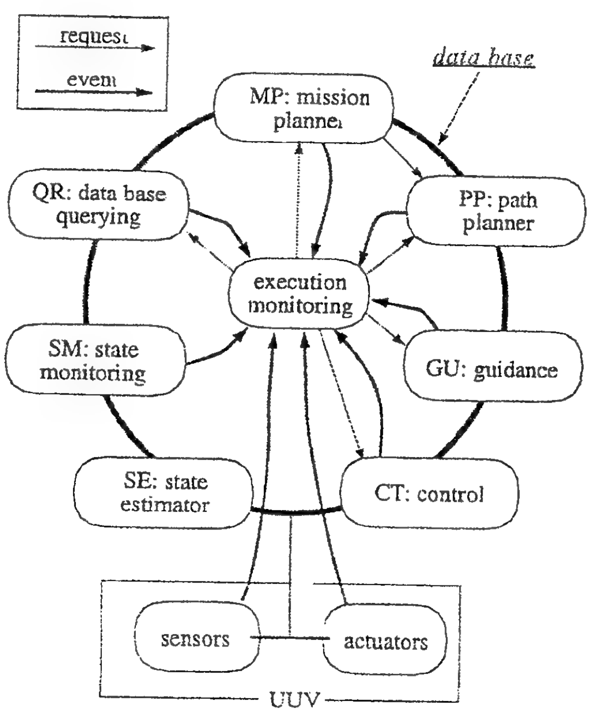
PROCOSA enables easy implementation of failure recovery procedures. This is a very important issue for autonomous UAVs as they have to cope not only with ordinary subsystems failures, but also with unexpected conditions in the environment, which make the current mission plan inadequate. Failure recovery procedures are specific behaviors planned in advance with which behavior or function to activate when such event occurs in such context.

Note that a function may consist in running some plan generation algorithm implemented in some compiled code on the on board computer. The software is based on an extended Petri net formalism (there is no action in the transitions). The Petri player interprets the events according to nets that are read at initialization.

In practice, data manipulated by the player have little chance to have compatible formats. For example, the

Behavior for plan updating





System Architecture

data structure will be different for a picture, a vehicle location, or an image file name. The Petri player needs to tackle this problem. Ideally, the LISP language is necessary that is why an interpreted lisp version has been developed, called TINY.

TINY is specified for on board applications :
- it keeps a safe behavior in case of run-time error,
- it has an easy interface with C,
- it reads several entries (sockets) in parallel.

Events are calling lisp function from TINY package.

The Petri net is in charge of the replanning behavior which is rather simple, even for a real implementation, because the representation sticks only to the replan logic and not to the complete algorithm.

PROCOSA has been recently interfaced with SAHARA in such a manner that it is possible to conduct the architecture and the software design in a unique formalism with validation properties.

PROCOSA has been experimented on various real implementations :
- real time (re) plan itinerary and trajectory of an underwater uninhabited vehicle called REDERMOR to reach areas of interest along a coast ;
- real time deck landing monitoring of a rotary aircraft. In this last case, the implementation was performed on a simulator.

When mission experts have reliably defined behaviors, PROCOSA is on the shelf for efficient execution monitoring implementation.

IV - optimization under constraints for continuous and discrete processes

The fourth topic concerns optimization tools ranking from short term scheduling, vehicle routing and resources dispatching to long term strategic planning. The software is developed and maintained by ILOG, a previous startup from INRIA also. ILOG, no longer a startup, is a well-known company involved in optimal aircraft routing for instance and is located at Bâtiment Orsud, 3-5 avenue Galliéni, 94 257 Gentilly Cedex, France ; phone / fax 00 33 149 08 36 00 / 10.

Since the company has recently edited a white paper on its software suite (see annex), this paragraph will only serve as a short introduction to the white paper.

UAV manufacturers and users will have a number of ways to take advantage of these new optimization algorithms :
- to tackle the problem of monitoring the UAV space allocation especially when UAVs are flying among manned aircrafts,
- to design a UAV, especially the payload allocation since one has to cope with small space for payloads, limited amount of energy, and more globally to optimize the severe cost efficiency objective,
- ...

The key to optimization is problem formulation. ILOG describes problems with decision variables, an objective function and some constraints functions :

◊ Decision variables represent parameters that need to be settled. They can be real variables, integer, logical, choices among a set of possible values, etc...

◊ The objective function describes the goal. They are of two different types : linear (leading to linear programming), or non-linear. This last category covers a very wide range of tradeoffs.

◊ Constraints functions describe logical or physical conditions that the decision variables must obey. In constraint programming, there are not only linear or non-linear expressions, but there can also be rule-based ones like "if A then not B".

The current linear and mixed integer programming algorithms are widely known but suffer limitations (heavy modeling, difficulties to solve large scale scheduling problems, limited means to guide the solution search).

ILOG suite based on constraints optimization combines the power of operation research algorithms with the flexibility and modeling capabilities of expert systems. Constraints-based system scale well into large problems spaces and yield results much faster than other techniques.

The ILOG suite has been used in the domain of transportation, telecommunication, manufacturing, finance, defense, and energy.

Conclusion

UAV systems are complex but will get more and more so, for example one can take the case of a HALE - High Altitude Long Endurance - UAV development. Sophisticated UAVs need to be designed and developed with the most recent software tools to master their complexity.

To have UAV systems expand to new market applications, especially civilian, UAVs will have to undergo severe airworthiness certification procedures. The use of those new tools should reduce drastically the cost of these procedures.

Usually, the cost of these tools is low, what is more demanding is to get into the habit to use them.

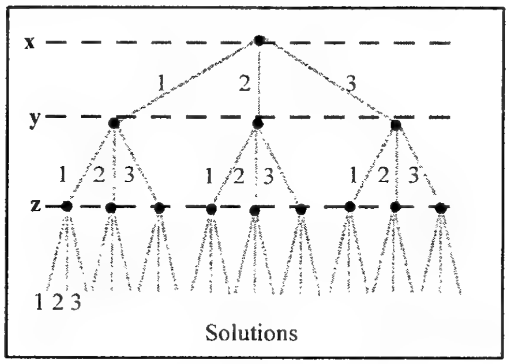
6. How The ILOG Optimization Suite works

6.1. Motivations Behind the Provided Optimization Techniques

This section gives an informal presentation of the main motivations behind the techniques implemented within the ILOG Optimization Suite.

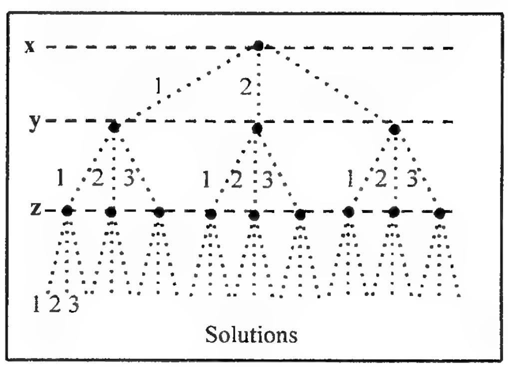
The basic algorithms used in the ILOG Optimization Suite rely on two simple ideas. The first is to explicitly represent the set of values that a decision variable can take. The second is to represent the search for a solution as a tree traversal.

The unknowns of a problem are represented as decision variables. Each decision variable in the ILOG Optimization Suite has a domain or a set of possible values. This domain can be infinite or finite, discrete or continuous. Solving a problem consists of finding the "right" values of its decision variables so that the constraints are satisfied and the objective function is minimized. To do this, the space representing all possible assignments of the variables must be explored. It is convenient to represent this search process in a tree diagram. The nodes represent variables and the branches represent the possible values of these variables.



The search space as a tree

When ILOG Solver follows a branch of a node, it assigns the value of the branch to that variable. Solving the problem consists of finding a path from the root node down to the leaves so that the constraints are satisfied and the objective function minimized.



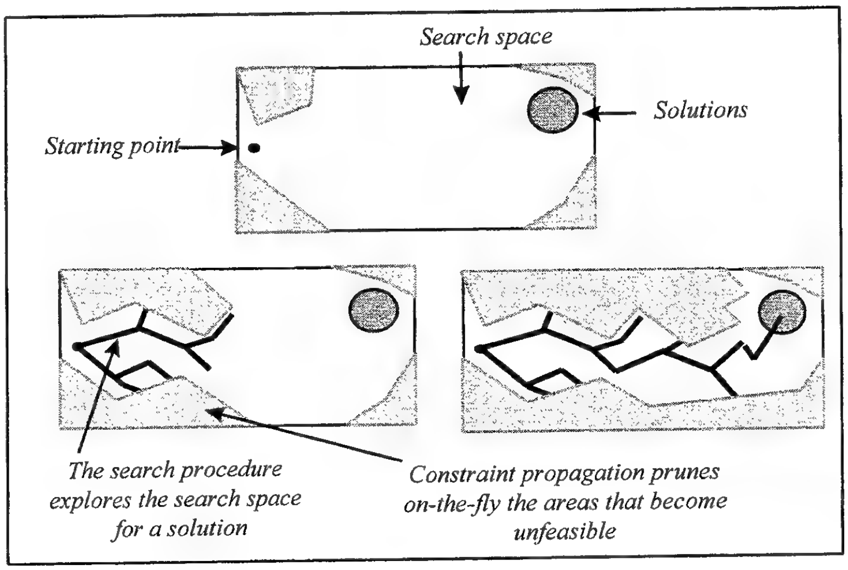
Exploring the search space

As you do not know in advance which branches will lead to a solution, you may need to explore all the possible paths from the root node down to the leaves. However, you cannot blindly try all the values in the domain of the variables, as this is totally unfeasible with real-

world problems. A problem with 10 variables and a thousand possible values for each of them has a search space with $1{,}000^{10}$ possibilities. Years of computational time are required to blindly explore this search space.

Finding a solution to a given problem is often difficult because of the problem constraints. Only a few paths actually satisfy the problem constraints, thereby leading to a solution. One way to overcome this difficulty is to use the problem constraints on the fly, in order to compute the consequences of each choice made on the remaining decisions. This reduces the combinatorial explosion of the search process. The problem constraints are, therefore, used to discover as soon as possible whether the followed path is wrong. This dynamically reduces the search effort still to be carried out, and obtains estimations on how far the search process is from a solution.

The ILOG Optimization Suite provides specific search algorithms that implement these features. Each time a value is tried, ILOG Optimization Suite algorithms deduce the consequences of this modification on the remaining variables, remove from their domains the alternatives that become unfeasible, and thus reduce the computational effort needed to find a solution. This process can be presented with the following diagram.



Search process

6.1.1. Domain reduction

As ILOG Solver, the core engine of the ILOG Optimization Suite, searches for a solution, it removes from the variable domains the values that are no longer feasible. Eliminating values that are no longer part of a solution is called *domain reduction.*

When the domain of a decision variable is modified, ILOG Solver uses the constraints to compute the consequences of this decision and remove from the domains of other variables the values that cannot satisfy the constraints and, therefore, cannot be part of a solution. The process of computing the consequences of the modifications and reducing the domains of the variables is called *constraint propagation.*

By reducing the domains on the fly, the ILOG Optimization Suite rapidly reduces the "combinatorial explosion" problem and avoids significant computational loads. The domain reduction process is implemented using the following principles. When you reduce the domain of a variable, you refine the information known about this variable. The ILOG Optimization Suite uses this information to update the set of possible alternatives for the remaining variables. This can be illustrated with the scheduling of maintenance activities. If you reduce the possible

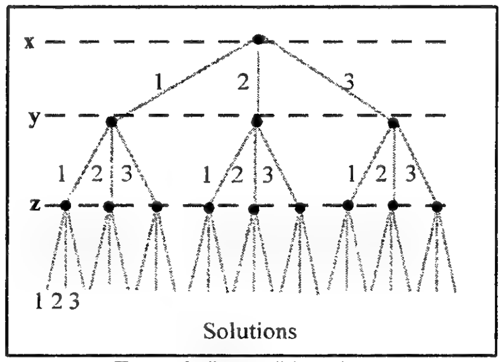
starting time of an activity so that it must be performed between June 3 and 5, you can deduce that all preceding activities must be finished by June 3 at the latest, and that all following activities start on June 5 on the earliest.

6.1.2. An example

Consider the following simple problem:

```
Find integer values for x, y and z such that:
    x ∈ [1,3], y ∈ [1,3], z ∈ [1,3]
        y<z, x-y=1, and x≠z.
```

The combination of all the assignments of x, y, and z is represented as a tree whose nodes represent variables and whose branches represent the possible values of those variables. Nodes at the same level represent the same variable.



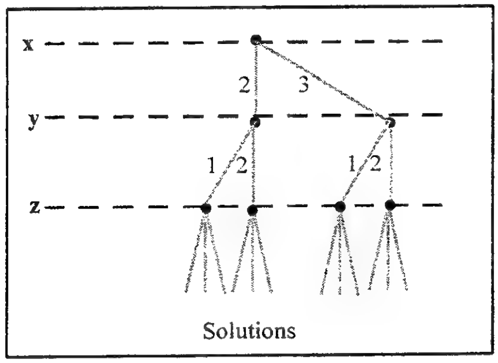
Tree of all possible values

This tree represents the search space - the space of all possible assignments. The set of paths from the root node to the leaves represents the combination of all possible assignments to x, y, and z. A possible path does not necessarily satisfy the problem's constraints, and therefore may not be a solution.

At this point, you can say that if there is a path from a root node down to the leaves that satisfies the constraints, then it is a solution to your problem. You can now apply the principles introduced in the previous sections.

6.1.2.1. Initial propagation

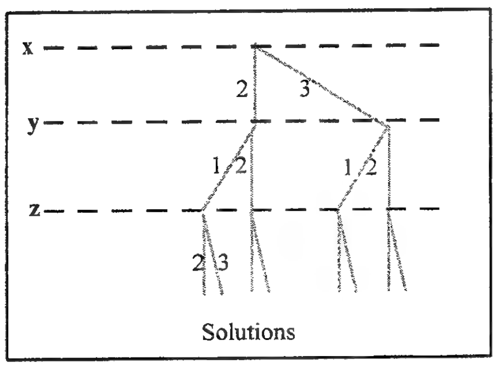
Consider first the constraint x-y=1. This constraint implies that the smallest value of x must be one unit higher than the smallest value of y. Therefore, 1 cannot be a possible value for x and is removed from its domain. The domain of x is now *[2, 3]*. Similarly, the maximal value of y must be one unit smaller than the maximal value of x, and the domain of "y "becomes *[1, 2]*. The domain of z remains unchanged since no constraints involve z at this point. You can update the tree by pruning the branches corresponding to the removed values. You obtain the following tree:



Pruned tree

If you now add the second constraint, $y<z$, the minimal possible value for z is 2, because z must be at least one unit higher than the minimal possible value of y. The domain of z is then reduced to *[2, 3]*, while the domain of y stays unchanged.

The updated tree is as follows:



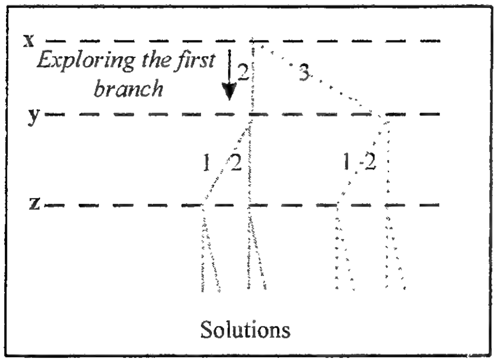
Pruned tree

When the third constraint $x \neq z$ is added, we can't apply any reduction on the domains of x and z. For now the domains of these variables remain unchanged.

The initial propagation of the constraints reduces the variable domains and prunes the search tree. However, the variables x, y, and z still have several possible values in their domains. You use a search procedure to explore the remaining branches in looking for a solution.

6.1.2.2. Finding a first solution

The tree search procedure will try the different values from the domain of these three variables. Assuming that the search procedure selects the variable x to start with and follows the first branch, when ILOG Solver follows the first branch, namely branch 2, it assigns the corresponding value to the variable. Here, the value 2 is assigned to x.



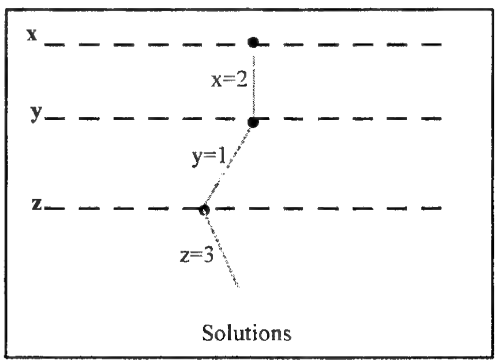
Exploring the search tree

At this point, constraints are automatically used by ILOG Solver in order to further reduce the other variable domains, if need be. As the domain of x has changed, the constraints $x\text{-}y=1$ and $x \neq z$ are activated:

- The constraint $x\text{-}y=1$ reduces the domain of y to the value 1. 1 is therefore assigned to y, as it is the only remaining possible value.

- The constraint $x \neq z$ removes 2 from the domain of z. The variable z now has one possible remaining value, namely 3. The value 3 is therefore assigned to z.

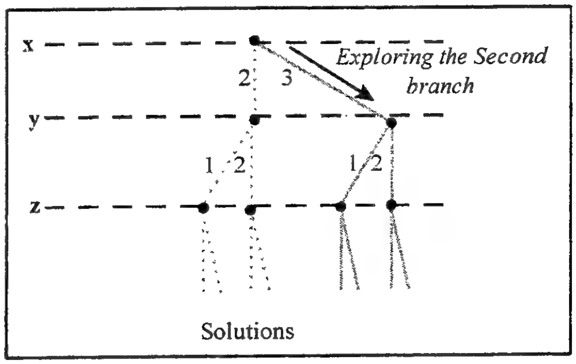
The 3 variables x, y, and z are all assigned and the constraints are satisfied. Therefore, the first solution to the problem is $x=2$, $y=1$, and $z=3$. ILOG Solver finds this solution after making only one choice.



The solution

6.1.2.3. Looking for other solutions

If you are looking for another solution, ILOG Solver backtracks. This means that it undoes the last decision it made and explores another branch of the tree. In the example, that decision was $x=2$. When ILOG Solver backtracks, the decision is undone, together with all its consequences. The domains of all the variables are restored to the state they were in before the decision $x=2$ was made. The variable domains are now $x \in [2,3]$, $y \in [1, 2]$, and $z \in [2, 3]$, and you are once again at the node labeled by x.



Backtracking and exploring the second branch

A new branch is followed, corresponding to the decision $x=3$, and the constraints are propagated once more:

- The constraint $x-y=1$ deduces that y must be equal to 2.

- The constraint $x \neq z$ removes 3 from the domain of z leaving 2 as the last possible value. 2 is therefore assigned to z.

- As the variables y and z have been modified, ILOG Solver activates the other constraints involving those variables. In this case, it is the constraint $y<z$. As the value of z is 2, this constraint sets the maximum of y to 1. Because y has yet to equal 2, an inconsistency is raised and triggers a backtrack. ILOG Solver deduces that there is no possible solution down this branch.

6.1.3. Efficiency of constraint propagation

The domain reduction process is used to reduce the search effort required to find solutions. However, the efficiency of this process, based on simple principles, depends heavily on its computing power and its capabilities to evaluate the global impact of decisions and to remove unfeasible alternatives as soon as possible from the search space. For this, the ILOG Optimization Suite integrates strong optimization algorithms. These algorithms can solve constraints, compute the global consequences of decisions, and drive the search process toward the targeted solutions.

6.2 The Provided Types of Variables and Constraints

ILOG Solver provides a rich set of variable types, constraint classes, search strategies and optimization algorithms. Objects are easily used directly by developers to model and solve resource allocation problems. The list of classes provided includes (and is not limited to) integer variables, floating point variables, Boolean variables, set variables, =, ≤, ≥, <, >, +, -, *, /, scalar product, subset, superset, union, intersection, member, Boolean or, Boolean and, Boolean not, Boolean If-Then, cardinality, distribute, extensively defined relations, trigonometric functions, power, square root, logarithm, exponential, as well as meta-constraints (conjunction and disjunction of constraints, order among constraints). You can also add new types of constraint to ILOG Solver by deriving new C++ classes.

To help you explore the search space, ILOG Solver provides a branch-and-bound algorithm and a backtracking search –chronological and non-chronological– together with a large number of search strategies. ILOG Solver also provides C++ classes and functions that implement non-deterministic programming. The latest functions can be used to implement any specific tree search algorithm.

6.3. Searching

Domain reduction is not enough to deduce the values of all the variables of a problem. For example, the problem under consideration may have several feasible solutions. A complementary search procedure is used to find an explicit solution to the problem in question.

6.3.1. Available procedures

With the ILOG Optimization Suite, you can explore the search space in several ways:

- You can use Solver to explore the tree search exhaustively, find the best solution to the problem, and prove its optimality.

- If you are looking only for a feasible solution or a set of alternative solutions to your problem, you can also use ILOG Solver to compute such solutions.

- You can also use ILOG Solver to gradually improve or repair a solution. The improvement process can be stopped at any time, and the best result found so far can be returned.

6.3.2. Searching and constraint propagation

The ILOG Optimization Suite intensively uses the constraints during a tree search to compute and propagate the consequences of each decision made. The constraint propagation engine of the ILOG Optimization Suite carries all constraints together during the search process. It computes the consequences of each decision taken by the search procedure or the user, tries to find inconsistencies as soon as possible, reduces the number of alternatives to be considered during the search, and drastically reduces the computational effort needed to find a solution.

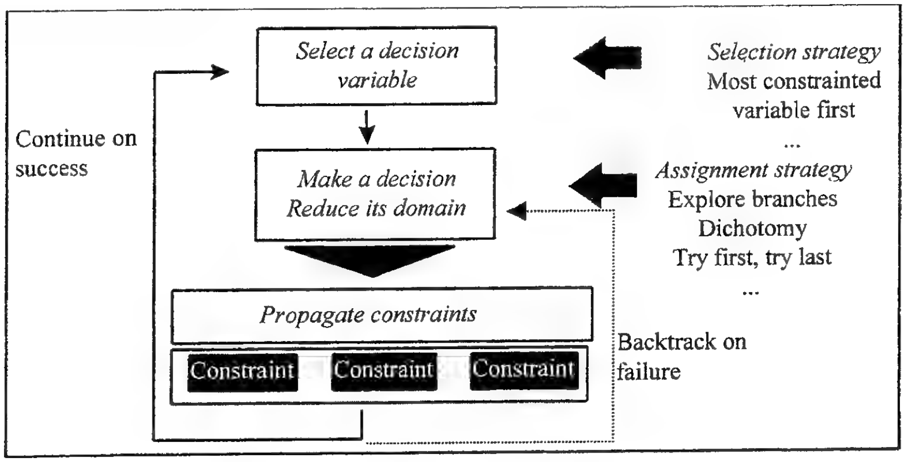
The exploration of a branch may lead to an inconsistency, that is, to a state where some variables have an empty domain. In this case, no solution is possible, and ILOG Solver automatically backtracks in order to follow another branch. Since no one knows which branch of the tree leads to a solution, ILOG Solver explores all the branches until one of them leads to a solution. In the example's case, the second branch of the tree does not lead to a solution. The first solution is the unique solution to the problem.

At each new node of the search tree, the constraints are used to reduce domains of decision variables. This domain reduction has two important consequences:

- The search strategy is improved because the set of alternatives coherent with the current partial solutions is dynamically and automatically maintained. Thus, alternatives that are obviously impossible are not considered.

- Inconsistencies are discovered early in the search process. As soon as a variable domain is empty, ILOG Solver knows that no solution can be obtained from the current branch.

These consequences are powerful enough to prune very large parts of the search tree, leading to superb performance. The search algorithm described here is implemented using the ILOG Solver function `IlcGenerate`. The order in which the variables are considered can be dynamically computed. For instance, a user can choose, as the next variable, the one that has the least number of possible values in its domain. This ordering among the variables does not affect the solution's validity but it can be very important for improving performance. The following figure illustrates the architecture of the search procedure.



Architecture of the search procedure

6.3.3. Implementing new search procedures

ILOG Solver also offers programming functions to create and explore the search tree in new ways. The tree-search algorithm described above can be implemented by two functions: branch and generate. Branch tries the different possible values from the domain of a variable. Generate takes an array of variables as arguments and calls branch to try values from the domains of those variables according to the following process:

1. As long as there are any unknown variables

2. Choose one of these variables

3. Choose a value to assign to this variable

4. Propagate the effect of that assignment; go back to step 1

There is a hidden problem in this description. In general, you do not know which value in the domain of a variable leads to a solution. Assigning a value to a constraint variable must be seen as a guess. If after this assignment an inconsistency is detected, it must be undone, and another value must be tried. This backtracking improves the previous algorithm as follows:

1. As long as there are any unknown variables

2. Choose one of these variables

3. Choose a value to assign to this variable

4. Assign the chosen value to this variable and memorize in parallel so that if a contradiction is detected afterwards, remove the tried and failed value from the variable domain and try another value; go back to step 1.

To express these search algorithms based on this try-backtrack on failure-retry mechanism, ILOG Solver provides goal programming.

The goals **Branch** and **Generate** can be implemented in the following pseudo-code:

```
ILCGOAL1(Branch, IlcIntVar, x){
 if (x.isBound()) return 0;
 IlcInt a = StrategyChooseValue(x);
```

```
  return IlcOr(x == a, IlcAnd(x != a,
                              Branch(x)));
}
ILCGOAL1(Generate, IlcIntVarArray, vars){
  int i = StrategyChooseVar(vars);
  if (i == -1) return 0;
  return IlcAnd( Branch(vars[i]),
                 Generate(vars)));
}
```

The important property of these goals is that they can be used to implement search algorithms other than the one used in `IlcGenerate`. In other words, they give the ILOG Solver user greater control over the actual search for a solution. Thanks to this extensibility, customers can incorporate domain-specific knowledge about the interaction among goals and constraints to provide very effective search accelerators. In fact, any tree-search algorithm can be expressed in ILOG Solver using goals.

6.4. About Constraint Propagation Algorithms

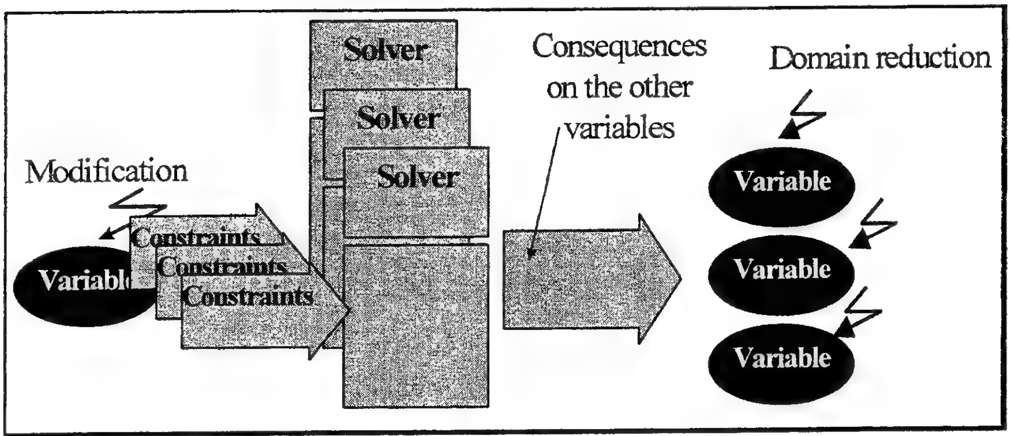
The constraint propagation algorithms carry out the reduction of the variable domains. The following sections describe how algorithms are implemented and perform this domain reduction.

Each class of constraints has its own algorithm, called the *solving algorithm*. An object, pointing to the decision variables that are involved in a constraint, implements the solver algorithm for this constraint. This algorithm removes from the domains of decision variables those values that cannot satisfy the constraint and therefore cannot really participate in a solution. Thus, each constraint keeps the variable domains consistent with its relation. Each constraint maintains its arc consistency. The word arc-consistency is used to emphasize the fact that a constraint is seen as an arc that links the variables together.

The solving algorithm of a constraint can also look ahead to the remaining possible values of the decision variables and check whether the constraint can be verified with these values. For example, take the constraint $x = y$ where x is smaller than *5* and y is greater then *10*. The solving algorithm immediately deduces that x and y will never be equal, because there is no intersection between the possible values of x and y. The ILOG Optimization Suite immediately reports this inconsistency.

6.4.1. Activation of the Solving Algorithms

When a constraint is posted on variables, ILOG Solver stores this constraint and activates its solving algorithm to update the domains of the variables in question. ILOG Solver also activates the solving algorithm of this constraint each time the domain of a relevant variable is modified. The solving algorithm then computes the consequences of this modification on the other variables involved by the constraint. This is the basis of the constraint propagation process described below.



Consequences on other variables

6.4.2. Constraint propagation

When the domain of a variable is modified, ILOG Solver activates the algorithm associated with the constraints that involves this variable. To stay arc-consistent, a constraint algorithm may reduce the domains of some other variables. This variable may be involved in other constraints that are then also activated for consistency. This activity is known as constraint propagation. The constraint propagation process is repeated until all the constraints are arc-consistent and no more information can be deduced from the modification. The constraint propagation process makes the constraints collaborate together in order to deduce as much information as possible from a modification of the domain of a variable. It is also one of the most important activities that the ILOG Optimization Suite handles automatically for you.

6.4.3. Arc-consistency algorithms

Generally in constraint-based optimization, various techniques are employed to remove values. ILOG Solver uses an extension of the AC-5 arc-consistency algorithm proposed in [DH]. The original AC-5 algorithm only handles integer decision variables, whereas ILOG Solver also handles set, Boolean and floating-point variables. This algorithm has been implemented very carefully because it is at the core of ILOG Solver's performance and accuracy. For instance, the constraints are not necessarily considered whenever the variable domain is modified. They are propagated only under certain conditions. For example, the constraint $y < z$ is activated only when the maximum possible value for z or the minimal possible value for y changes. No other reductions of the two domains would lead to additional reduction of any of the domains. For this reason, the constraint does not need to be activated. When compared to other constraint propagation implementations, ILOG Solver is seen to be more than 2,000 times faster [P.L].

6.5. Using Simplex Algorithms with ILOG Planner

6.5.1. Why simplex algorithms?

The family of simplex algorithms has proven to be very efficient in real-life applications that let you build a linear model of your problem; that is, when the model contains mainly linear constraints. ILOG Planner has been designed to profit from the efficiency of these algorithms in applications in which a lot of constraints can be placed in a linear form. ILOG Planner can significantly speed-up the ILOG Optimization Suite. This allows for addressing more efficiently particularly big or difficult applications.

ILOG Planner includes primal, dual and network simplex algorithms, and benefits from CPLEX algorithmic know-how.

6.5.2. Basic principles of ILOG Planner

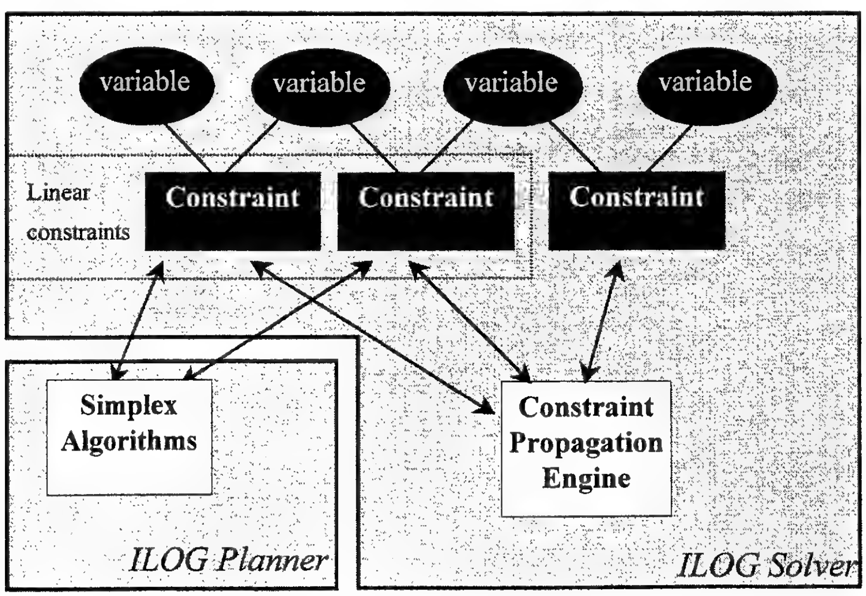
ILOG Planner shares the variable and constraint objects of ILOG Solver, allowing it to benefit from the elegant C++ syntax provided by Solver.

The way ILOG Planner and ILOG Solver work together is based on the traditional branch and bound procedures used to solve integer problems in linear programming. Basically, a linear relaxed problem is used to provide an approximation of the optimal solution. For a minimization (maximization) problem, this approximation provides a lower (upper) bound of the cost function. Then, the optimal relaxed solution computed by the simplex algorithm may be used to guide the search procedure.

6.5.3. How ILOG Planner works

ILOG Planner implements the following mechanisms. First, you notify ILOG Planner of the linear constraints in the problem to be solved. Then, the simplex algorithm of ILOG Planner computes the optimal solution (if any) of the problem, and sends the optimal cost value to ILOG Solver, which updates the domain of the cost variable accordingly. Finally, a search procedure built with the search facilities of ILOG Solver may use the optimal relaxed solution provided by ILOG Planner as an approximation of the optimal solution. Late during the search, when the search procedure deduces or tries new bounds on a variable, ILOG Solver sends the new bounds to ILOG Planner, which updates the relaxed solution according to this bound modification and computes the new minimum value of this cost function.

You don't need to model your problem using only linear constraints to take advantage of ILOG Planner. That's why ILOG Planner is particularly well suited to problems for which linear programming techniques are not applicable but involve a lot of linear constraints.



Revised simplex procedure

7. Benefits of The ILOG Optimization Suite

Constraint-based optimization and especially the ILOG Optimization Suite have been successful implemented in very diverse projects. In this section, we analyze the current successes of constraint-based optimization, and characterize the types of problem in which it can be applied.

7.1. Interactive and Reactive Search Capabilities

The ability to define constraints and variables and find a solution is not enough for a lot of practical applications. Users may need to intensively interact with the planning applications. They would need, for example, to generate several plans, explore scenarios, run simulations and what-if analyses, and add or relax constraints. In other applications, *reactivity* is a key issue. It means that the planning applications must be able to update plans according to new data, new constraints or new priorities.

To satisfy these requirements, the ILOG Optimization Suite provides a way to *manage* constraint models. ILOG Solver provides a mechanism, the *manager*, which allows adding and removing constraints, completely or partially storing the current solution, and restoring the previously stored partial or complete solution.

Moreover, another benefit of the ILOG Solver manager is the possibility of writing advanced optimization algorithms relying on a limited search in a subtree, iterations on local optimization, problem decomposition, etc.

7.2. Programming Search Strategies

The core technology of the ILOG Optimization Suite has several benefits. The ILOG Optimization Suite actively uses constraints and removes the unfeasible alternatives from the variable domains on the fly. In this way, the ILOG Optimization Suite converges on solutions much faster, systematically reducing the number of possibilities to be explored. The domains of the variables are constantly updated during the search, providing very useful information for refining the search strategy.

A more general advantage of the search technique used in the ILOG Optimization Suite is that the search strategy is independent of the constraints and can be programmed. The next decision variable to be explored is identified dynamically once all the constraints involved in the current node have been propagated. The order in which the nodes of the search tree are explored is therefore dynamic and programmable with the ILOG Optimization Suite.

7.3. Improving Solutions

With many problems, you can find an initial solution very easily. However, to find an optimal solution and verify its optimality, you usually need long running times. For these problems, you can easily implement a search using the ILOG Optimization Suite algorithm that generates a preliminary solution very quickly and then gradually improves the result. This approach can be stopped at any time, with the best result found so far returned.

7.4. Exploiting Problem Knowledge

As a user of the ILOG Optimization Suite, you can make the search itself more efficient by exploiting knowledge about the problem. For example, the order in which the nodes are explored in the tree may be very important. Consider the timetabling application for mainframe operators at the Banque Bruxelles Lambert. Some parts of the year are more difficult to schedule than others. Normally, many engineers want to take their vacations in the summer

and around Christmas. It seems reasonable, therefore, to assign the shifts corresponding to the Christmas week first, as this is the week in which the problem is the most difficult to solve. This kind of information is called "strategic knowledge," since it deals with the way the problem should be solved.

Strategic knowledge is quite easy to use with the ILOG Optimization Suite. In fact, if you look at the basic search algorithm, The ILOG Optimization Suite enables you to control the order in which the variables are selected. This principle can be applied to dramatically improve performance on very complex problems.

7.5. Integration of Operations Research Algorithms

A very attractive property of the ILOG Optimization Suite is that it easily integrates specialized algorithms for solving a given problem. In other words, constraint-based optimization is a framework for cooperating problem-solving algorithms. Algorithms are implemented as constraint solvers, and the custom algorithms and standard solvers communicate via the variables.

There are several algorithms already integrated in the ILOG Optimization Suite. This section now describes two of these algorithms: the revised simplex and the edge-finder.

7.5.1. Revised simplex for linear constraints

Linear Programming algorithms with the simplex procedure are widely used in solving linear problems such as liquid blending and production planning. ILOG Planner complements ILOG Solver by providing a simplex solver to handle problems that involve many linear constraints or can be represented with linear models. ILOG Planner handles linear constraints while ILOG Solver algorithms handle logical constraints.

ILOG Planner solves the problems that occur in the standard linear programming approaches: integer and mixed-linear integer programming. When looking for solutions, ILOG Planner relies on the search procedures of ILOG Solver. It benefits from all the flexibility of the ILOG Solver functions in driving the search, implementing search strategies and solving directly logical constraints.

7.5.2. Resource constraints for scheduling applications

For scheduling problems involving time and sequencing, the edge-finder algorithm is implemented in the finite-capacity resource constraints of ILOG Scheduler. This algorithm is one of the most successful operations research algorithms for rapidly updating time windows of activities submitted to resource constraints. This innovation incorporates the efficiency of this algorithm with the flexibility of constraint-based optimization.

7.5.3. User-defined global constraints

You can define global constraints, that is, constraints shared by a set of variables. An example of this is a resource allocation problem such as assigning cashiers -to work areas (i.e., cash registers) in a department store.

Two cash registers each require two people. In ILOG Solver, the model for this problem includes two decision variables, one for each person. The possible values for these variables are the cash registers. The only constraint in the problem is that no variable pair can be assigned the same cash register. This is simple and intuitive.

In some systems, this restriction might be expressed by stating a different constraint for each variable pair. However, if n is the number of people, must you then have n^2 constraints? Stated

this way, the problem model is unnecessarily complex and consumes an enormous amount of memory and processing time. Indeed, if you have 1,000 people in a chain of stores, you would have to create 1 million constraints.

An alternative provided by ILOG Solver is to use only one global constraint and share it with all the variables. The space required by the constraint is linear with respect to n.

7.6. What About Other Techniques?

It can be argued, though, that the problems tackled by the ILOG Optimization Suite are intractable. (They are often known to be NP-hard.) In other words, certain problems may take an exponential amount of time to solve. Fortunately, this issue rarely occurs in practical real-world situations.

First of all, our experience at ILOG has shown that such "intractable" problems are already partly solved manually. Usually the solutions are not automated but the problems cannot be represented satisfactorily with less-expressive problem solvers. Indeed, these problems require all the expressive power of the ILOG Optimization Suite in order to be represented accurately enough.

Those solutions that can be represented with less-expressive packages are already solved by those packages, and consequently the solution is "good enough," although it may be improved upon. The ILOG Optimization Suite can generate exactly the same solution using the same imprecise problem definitions. Thus, although a purely optimal solution to the problem is not currently needed, using the ILOG Optimization Suite still allows more maintainable code and easier expansion to meet future needs.

Another important issue is the environment in which resource allocation systems must be integrated. Most ILOG Optimization Suite applications are not batch applications that read data and then produce a solution. They are decision-support applications. Indeed, they often present an interactive graphical user interface when displaying a solution. In these applications, users want to see the current solution and monitor the search algorithm. They may even want to stop the search, remove or add constraints, and start the solution search again at a given point.

DESIGN AND AIRWORTHINESS REQUIREMENTS FOR MILITARY UNMANNED AIR VEHICLE SYSTEMS

(Sept 1999)

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Please note: Any views expressed are those of the author and do not necessarily represent those of the Department/Agency

ABSTRACT

This paper examines the safety implications and factors to be considered for the procurement of a UAV and identifies the design requirements to be used as a guide to produce an air vehicle specification. It will touch on matters covered in more detail by other presenters because of the need to reflect the information they provide within the new standard. It should be noted that while appreciating that dirigibles and micro UAV's will be introduced in the future, it was agreed that the current UK Defence Standard 00-970 should comply with current policy agreed within the United Kingdom (UK) Ministry of Defence (MoD), and that by the Civil Aviation Authority (CAA), which is, that UAV Systems under 20kgs should be treated as models and as such do not need to comply with the regulations governing aircraft. This paper also identifies the role of the "Airworthiness, Design Requirements and Procedures (ADRP) organisation" of the UK MoD Defence Procurement Agency (DPA) and details the work being carried out in developing a set of general design and airworthiness requirements for UAV systems. ADRP are part of the new Defence Procurement Agency (DPA). which was formed on the 1st of April 1999, to take forward the "SMART" Procurement initiative, which aims to use faster, cheaper and better ways of equipping the UK armed forces. This involves Integrated Project Teams (IPT) managing the programmes throughout the life of the equipment. This paper discusses the current and future UAV Systems requirements and gives a brief insight into the strategy adopted to produce a set of regulatory documents and procedures for the guidance of the MoD Integrated Project Team leader (IPT/L). This is done by ensuring adequate procedures are in place for the safe and airworthy operation of such aircraft. These procedures set the minimum standard required to accommodate the safe operation of all UAV systems in all airspace conditions subject to any limitations and constraints imposed by the design.

INTRODUCTION

This paper discusses airworthiness activities and the set of procedures which are being produced by ADRP. It is not intended that these procedures should solve all the problems relating to the introduction of UAV Systems (UAVS) however, the documentation being produced should form the basic building blocks from which future UAV's will develop. This paper will also identify and describe some of the activities being undertaken by ADRP and the Unmanned Air Vehicle System Sub-Committee (UAVSSC) relating to airworthiness and design, and to identify those areas of concern that need to be addressed to ensure safety in the air and on the ground. The paper, although generally based on my own thoughts and opinions also reflect the policies and procedures agreed within MoD.

SAFETY CONSIDERATIONS

The requirement to fly military UAV Systems (UAVS) in civil airspace is being addressed but I understand that it may be some time before a comprehensive policy is formulated and is incorporated into Air Navigation Orders. From my own point of view I would like to see four levels of operation, these should be:

a. Military controlled ranges - where civil aircraft are generally excluded from flying;

b. Civil airspace below 3000ft/10000ft (depending on area) where see and be seen is of the utmost importance.

c. Civil airspace 10000ft-24500ft Used by most commercial airlines and under Air Traffic Control

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.

d. Civil airspace above 24500ft - Although some commercial aircraft fly at these heights this is considered uncontrolled airspace.

From the above levels of operation can be identified three distinct types of UAV. Figure 4 (attached as an Annex) identifies three levels of sophistication depending on application. Area of operation, size, and endurance of the system need to be considered as this will effect cost, why use a complex system if durability and safety of personnel are not a issue?!

If we first look at the problems associated with flying military UAVS on ranges for training or as targets, in general suitable regulations can be produced. The solution adopted is to have a set of regulatory procedures which include extensive testing, restricting the spread of personnel on the training area under the flight path and the introduction of cut down mechanisms and other fail safe devices, however if you are flying over the civilian population the solution becomes far more complex. The types of UAV likely to be used will be varied in size, weight, range and complexity. As I see it there will be an on going need to interface and interact with other organizations such as the Civil(CAA) and Federal(FAA) Aviation Authorities, local Air Traffic control and possibly the civic authorities over whose area the UAV is being over flown if emergency landing areas are to be identified.

Under the general heading of Safety I have addressed those aspects which I feel need to be considered. This list however is not exhaustive and I am sure will be added too. For this presentation the term **Safety** includes the following elements.

a. **Airworthiness.** - Embraces such factors as: Reliability, System Maintainability, The use of approved designers and manufacturers, crew training, Controllability, Recovery, Commands and control links. If we look at these areas in more detail, taking into account the future need for UAV's to fly in civil airspace in peace time, the designer will need to consider:

(1) System Reliability - comply with the requirements for manned aircraft as far as system reliability and maintainability is concerned. Where possible critical systems should be duplicated. The use of redundant systems will only be possible on the larger UAV's where the weight factor will be less of a problem.

(2). Structural Failure - To prevent structural failure all components forming the airframe (whether modular or not) should if possible be dynamically tested, this testing should be commensurate with the size and type of UAV.

(3) Manufacturers - In the UK there are few dedicated UAV manufacturers, however most of the big companies have been involved with control systems, Guided Missile production, test and evaluation procedures which should be similar for UAV systems taking into account the need for durability and reusability.

(4) Controllability - is a major area of concern, the interruption or corruption of signal commands and data links to and from the UAV is an area which further work is required and STANAGS are being produced. The loss of signal during conflict can be embarrassing as well as costly especially if the result is the loss of a number of UAV's. In parallel to this, in the model aircraft world, cases have been reported of interference by high powered electronic equipment operation causing models to fly erratically and in some cases causing injury and death.

(5). Approved training schemes for personnel are being implemented. With the operator/pilot being remote from the UAV, as well as the need to operate the system correctly there is also the need to ensure that personnel have instilled in them the fact that their actions could directly affect the health and safety of third parties on the ground and in the air .

(6) Recovery, planned or emergency. When, in future, we start to fly UAV's in civil airspace on a regular basis the problems of landing safely will be of paramount importance. By this, I don't mean the need to land the UAV at the end of a mission. If a problem develops with a major sub system such as the engine or receiver/transmitter when flying over a populated area, the last thing that you want to happen is for the UAV to cut down immediately. It would seem therefore that either emergency landing areas along the route should be identified or diversions around high density areas must be programmed into the onboard computer. Steerable parachutes controlled by GPS could be one way of getting around the problem of where to land. The use of specified areas such as Parks or reservoirs as possible emergency landing ground along the route should be considered and this information programmed into the onboard computer.

b. **Airspace Management** - The UK Airspace Steering Committee has working groups looking at the

problems of flying UAVS to the current Air Navigation Orders (ANO) such as **See and be Seen** and **See and Avoid**. Conspicuity is another matter, is camouflage really necessary in peace time? Should the UAV be controlled or autonomous (how involved should the man in the loop be?) And finally should there be timed exclusion zones along the flight path of the UAV? All these questions have an impact on airworthiness and the design requirement.

(1) I see the flying of UAV's below 10,000ft, as being the major problem area as this is used by general aviation and low flying military aircraft. Helicopters and other light civil aircraft may even be below 500ft in certain areas. Most UAV's will be flying between Zero to 2000ft. The ANO requires a minimum separation of 500ft between aircraft, the ground, any obstacle or person, this could create a problem when in VFR(see 3 below).

(2) There is a need for the UAV to communicate with ATC especially when "operating in" or "transiting through" controlled airspace. There is also a need to recognise other airspace users. A dedicated UAV controller (possibly retired aircrew) to act as liaison with the ATC may be the answer.

(3) The ability to **see and be seen**. or **see and avoid** is the major problem. Most military UAV's will be camouflaged and designed for low visibility (possibly visual and radar signature), essential for operational purposes. In addition unless they are like Predator or Global-hawk they will be smaller than a manned aircraft and likely slower. If other small manned aircraft are operating in VFR it will be difficult for these pilots to identify the approaching aircraft as a UAV, and assess the separation distance. The fact that it cannot comply with the rules of the air to avoid a collision means that it will be necessary to indicate to other airspace users that the aircraft is a UAV. Some UAV systems use cameras for flying, the operator having direct control of manoeuvres, however there will always be blind spots which will affect safety. The fitting of Transponders to all UAV's will not alleviate the problem as not all civil owned aircraft have them fitted, or switched on, or have the means to pick up external signals. The use of timed exclusion zones for other traffic may be worth considering as a method of reducing the risk of collision.

(4) <u>For Visibility/Conspicuity</u> - high intensity strobe lights have been suggested however as well as the weight penalty, you may need more than one to ensure that all angles of visibility are covered. This solution is impractical for the smaller UAV Systems for several reasons including, weight and power consumption I suggest that anything smaller than the UK Phoenix would be impractical. To have separate aircraft for peacetime could be one solution (forgetting the strobes), discussions into the colour to be used, are taking place in the UK. The colour scheme to be used should take account the heating effect of solar energy. It is suggested that painting any UAV's "Black", like current training aircraft could affect electronics and mechanical actuators close to the external skin.

(5) <u>Man or Machine Operation</u> - For flight safety purposes I cannot see that there is much to gain by having a man in the loop flying the UAV during transit from the launch area to the target location. His visibility will only be that shown on the screen by the selected camera, I can see a certain amount of disorientation if more than one camera is fitted, and the controller is constantly switching between cameras (see and be seen aspect), especially with the medium to long range UAV systems.

c. <u>Health and Safety</u> In the United Kingdom legislation is in place on health and safety. The Secretary of State for Defence has stated that the MoD will be subject to the requirements of the current legislation, therefore personnel, and equipment (throughout its life cycle), provided for and/or operated by the Services must comply with current health and safety. The equipment life cycle will include all elements of: design, supply, manufacture, operation, maintenance, testing, storage and disposal.

<u>Operational</u> - This is very much a chicken and egg situation, what comes first? Should we be looking at our needs/requirements or should we be looking at what's on offer and adapting it to our needs. What is the most cost effective method? Some of the criteria to be considered are:

(1) <u>Tasking</u> - the questions to be asked does the task require the UAV be flying, low, medium or high level and is it required for short, medium or long range use. The type of sensors to be fitted will also have an impact on how the UAV is treated. In case of failure during operations, does it need to be destroyed or can it be recovered?. Another factor which will have an impact on design is will it accompany manned aircraft, fly solo or be part of a group of UAV each having different functions.

(2) Environment. - Will the UAV need to be operational in all climates or can it be tailored to suit specific areas?

(3) User - whether the UAV is ship launched, ground launched or dropped or ejected from an aircraft needs to be determined and the design of the UAV and its system adjusted accordingly.

(4) Interruption or corruption of signal commands. - I have already iterated this point once, however the hardening of the system although a costly exercise maybe necessary.

THE ROLE OF ADRP

The role of ADRP is to:

- **Provide airworthiness and safety services to all involved in the procurement and operation of UK military aircraft.**

To achieve this we:

- **Assist those with responsibility for military aviation safety to establish and maintain the high standard of safety demanded of the aviation business by:**

    * **providing effective support to the Defence Aviation Safety Board (DASB) and the Joint Airworthiness Committee (JAC).**

- **Assist DPA, the Chief of Defence Logistics (CDL) and operational staff to achieve their mission in a better way, consistent with achieving high safety standards, by promulgating and advising on:**

    * **DASB policy**
    * **airworthiness standards and procedures,**
    * **Best safety management practices.**

ADRP organisation chart (see Fig 2).

With increased interest from the three Services to operate UAV Systems and the need to fly UAVS outside of military controlled ranges it is of the utmost importance that high integrity proven systems are used and operated correctly. This is best achieved by providing a set of regulatory documents for all to use. It is in the design area that the Airworthiness Design Requirements and Procedures (ADRP) Branch of MoD Defence Procurement Agency (DPA) has a major role to play.

The Branch is split into three sections under the Assistant Director (AD)/ ADRP, these are ADRP1 (Policy), ADRP2 (Procedures) and ADRP3(Weapon Airworthiness). The function of the three sections is as follows:

ADRP1 (Airworthiness Policy and Procedures)

Tasks Include:

- **Secretary to the DASB**
- **Internal Audits of Aircraft Projects**
- **Controls the register of all UK military aircraft**
- **Joint Service Publication (JSP) 318B Regulation of Ministry of Defence Aircraft**
- **Def Stan 05-122 Military Listing of Civil Owned Military Aircraft (COMA)**
- **Airworthiness Training**
- **advice on Safety Critical Software and Y2K matters.**

ADRP2 (Airworthiness Design and Procedures)

Tasks Include:

- **Production of Def Stan 00-970, 00-971, 00-932, 00-933, 05-123 and Airworthiness elements of 08-5.**
- **Management of the Design Approved Organisation Scheme.**
- **Secretariat of the JAC**
- **Focal point for SBAC and Industry**
- **Focal point on Standardization**

ADRP3 (Armament Airworthiness and Safety)

Tasks Include:

- **Professional advise to aircraft platform offices/IPT's on Armament Safety, Airworthiness and related subjects.**
- **Provide advise on the application and amendment of MIL STAN 1760.**
- **Advise on the safe integration of weapon systems.**
- **Provide assistance to ADRP1 and 2 on weapon safety policy.**
- **Assist the Defence Logistics Organisation (DLO) with advise on Armament matters.**
- **Involvement with the preparation of a new MIL STAN on Miniature Munitions.**
- **Maintain a Weapon MA Release and COMA data base.**
- **Review of environmental testing of armament stores.**

DEFENCE AVIATION SAFETY BOARD (DASB)

UK military aircraft (including UAVS) operate under the Crown Prerogative that is they are not regulated by an act

of Parliament. However The Secretary of State (SofS) for Defence has a duty of care to ensure that the procurement, maintenance and the operation of military aircraft is carried out in such a way as to ensure safety. This duty is discharged by employing a regulatory system and supporting procedures, with the intention that they should be no less effective than that required for civil aircraft. The DASB is established to assist the SofS in discharging his airworthiness responsibilities by directing airworthiness policy and providing advice to the SofS, Single Service Chiefs, Chief Executives' (CE) of DPA and DERA. Its members are drawn from all three armed services (both in operational and engineering capacities) and includes senior representatives from DPA and the Defence Evaluation and Research Agency (DERA). AD/ADRP is the group secretariat, and consequently is the air system focal point for the promulgation of airworthiness policy.

DASB Terms Of Reference (TOR)

- **Provide top-level advice on Aviation Safety.**
- **Inform MoD top-level management on Aviation Safety.**
- **Call for and consider reports as appropriate.**
- **Co-ordinate and review MoD Aviation safety policy.**
- **Recommend where appropriate revisions of Airworthiness delegation.**

The DASB has five subordinate committees dealing with the specific tasks identified below and in **Figure 1** (attached - the DASB organizational Chart down to working group level). Depending on the type and the scope of the UAV to be used, it will be discussed at the appropriate committees.

DASB Committee Structure

DASB

- **ASIG**
  (Aviation Safety Implementation Group)
- **FWAMG**
  (Fixed Wing Airworthiness Management Group)
- **HAMG**
  (Helicopter Airworthiness Management Group)
- **MoD/CAA PSG**
  (MoD/CAA Policy Steering Group)
- **JAC**
  (Joint Airworthiness Committee)

However for the purpose of this presentation we will only be concerned with the Joint Airworthiness Committee structure, which is chaired by AD/ADRP

The Joint Airworthiness Committee (JAC)

Chaired By AD/ADRP

Membership:

MoD Project Staff
SBAC Members
DERA
Sub-Committee Chairpersons
CAA
ADRP Technical Staff

This committee first established on the 2nd Feb. 1940 allows consultation between Industry (SBAC) and MoD on matters of airworthiness and military aircraft safety (this includes equipment and associated services). In particular the JAC is charged with endorsing technical design and certification standards for military aircraft, and joint MoD/Industry processes and procedures for the procurement and maintenance of military aircraft.

Airworthiness and safety tasks of the JAC include:

- **Reviewing the impact on military aircraft of new revised MoD policies and practices, recommending changes to improve airworthiness or safety.**
- **Examines, reviews and recommends where appropriate the application of emerging civil aviation and central Government policies and practices and requirements to military aircraft.**
- **Considers and recommends where possible, the application of best practice in assuring airworthiness and safety to military aircraft.**
- **Ensures a common and co-ordinated approach to the use of European, International and National standards for MoD procurement in the aerospace sector.**
- **It will initiate and progress changes to MoD Technical Documentation arising from emerging technology or aircraft incidents/ accidents to assure the airworthiness and safety of military aircraft**
- **Once the JAC has ratified papers produced by its sub-committees or consultants, ADRP carry out all necessary action to ensure that the papers produced are inserted into the relevant Defence standards 00-970 or 05-123 (Procurement Procedures for Aircraft).**

It is appropriate at this stage to define airworthiness, especially as airworthiness appears to have a slightly different meaning depending on who you talk to. The UK MoD definition of Airworthiness is as follows.

Definition of Airworthiness (from Joint Service Publication (JSP) 318b

Airworthiness is the ability of an aircraft or other airborne equipment or system to operate without significant risk to aircrew, ground crew, passengers (where relevant), or to the general public over which such airborne systems are flown.

For an Unmanned Air Vehicle (UAV), airworthiness embraces a number of elements or sub-systems not normally associated with flying aircraft. I refer of course to the ground/sea/air "Support Facilities" which may consist of the control station, launch mechanism and the transmission systems for the control link. The complexity of the system and the theatre of operation in which the UAV is going to be used will have an impact on the design factors necessary to achieve airworthiness. It should be noted that the design, build and maintenance elements are implicit in this definition of airworthiness.

While on the subject of definitions, throughout this paper I have used the term "Services" with a capital "S" this refers to the Navy, Army and Airforce of the United Kingdom

MILITARY AIRCRAFT RELEASE

7.1 Before any aircraft can be released to any of the three Services it has to receive a Military Aircraft Release (MA Release). The MA Release identifies the flight envelope in which the UAV is safe to fly. The procedures to be adopted are set out in the Joint Service Publication JSP318B, Regulation of Ministry of Defence Aircraft.

The M A Release covers:

- **Airworthiness and Document Management.**
- **Aircraft Design and Handling Limitations.**
- **System Limitations and Constraints.**
- **Audit Trail.**

The MA Release is the military equivalent of the CAA "TYPE" Certification. The initial **MA Release** is issued under the authority of the Chief Executive (CE)/DPA, who delegates responsibility to the MoD Integrated Project Team Leader (IPT/L)/Aircraft Project Director (APD). The IPT/L will only recommend issuing the MA Release once he/she is satisfied that sufficient evidence exists to establish the airworthiness of the aircraft. Such evidence would include: a Certificate of design signed by an approved signatory for the Contractors; all supporting documentation and procedures for the design and construction of that the aircraft /Equipment, comply with the requirements of the specification and all standards identified therein; The IPT/L(APD) will request an assessment independent of the designer to establish confidence in the airworthiness of the design. This may be carried out by DERA Boscombe Down or any other approved aircraft assessment organisation. All activities are documented and the design, handling, role, system limitations and constraints are set out so that a comprehensive audit trail can be maintained.

The MA Release is then passed to the Service Operational Branch who issue the **Release to Service** (RTS). Initially this is normally a copy of the MA Release with a new cover. The RTS authorises flying under the control of the Chief of Staff (COS) for that Service. At some point after entry into Service, the Service may wish to change the operating limits either to save on fatigue life or to extend the limits to cover some specific short term mission capability or because they wish to embody a **Service Engineering Modification** - such alterations are covered by Service Deviation and the parent Service accepts full responsibility for the airworthiness of these deviations.

HISTORY OF UAV's IN SERVICE

The early pioneers of manned flight had their problems, especially with structural integrity. The materials used, the methods of construction, and the design concepts that were applied resulted in several incidents involving the pilot and also innocent bystanders. In the early years the UK National Physical Laboratory were concerned with aerodynamics and structural strength for military aircraft, as a result of this and other activities, the Handbook of Strength Calculations (HB 806) was produced and further developed during the 1914-18 war. This document has evolved over the years through Air Publication 970 to the current Defence Standard (Def Stan) 00-970 (discussed later). However even with the best design techniques and maintenance procedures, mechanical failures still occur, and some of the more dramatic modern failures are those associated with electronic control systems. The introduction of new technology to control aircraft, such as fly by wire/light and computerised operating systems with no mechanical backup, has brought about its own problems.

The need to consider the control of Software and other factors such as Electro-Magnetic Interference (EMI) and for equipment to be hardened against this effect, whether it is natural or induced by man has to be considered. Aircraft system failures can lead to spectacular results as well as being both costly in life and equipment as shown in the video. Although these incidents relate to manned aircraft similar situations could arise with a UAV's. The risk to life in populated areas must be taken into account whether training or operating as part of a peace keeping force.

When you consider that the first unmanned Aircraft flew in the UK around 1913, it has taken the UAV a long time to progress especially when you compare with manned flight. However the UK has flown a limited number of UAV Systems over the years mostly as targets or target towing aircraft, the exception being the "Midge Drone" (CL 39) Reconnaissance UAV, the Army's predecessor of Phoenix.

Falconet, Chuker and Jindivik to name but a few have been used by the three Services, however all these systems were and are still restricted to cleared ranges. Jindivik, which is primarily used to tow targets, is the one exemption to the rule as this has to travel for a very short period of time in an air traffic zone when in transit between the airfield and the range. To do this it is accompanied by a manned shepherd aircraft, usually a Hawk. The shepherd aircraft accompanies Jindivik throughout its flight into the range but withdraws when the missiles are being fired at the towed targets. On the completion of firing the shepherd aircraft rejoins the Jindivik and carries out an airborne inspection of the airframe to ensure that the air vehicle has not been damaged during the firing, and is recoverable. It should be noted that this inspection is carried out prior to leaving the range.

The Directorate of Flying is responsible for regulating all non service flying of UK military registered aircraft, including UAV Systems this includes private ventures using MoD ranges.

DESIGN APPROVED ORGANISATION SCHEME (DAOS)

To ensure that safety and airworthiness are addressed at the design stage, the UK MoD have a set of procedures which are employed to select companies that are capable of carrying out the tasks required. The competence of design of the potential UAV contractor will be assessed, under the Design Approved Organisation Scheme (DAOS). Information on this scheme is contained in Def Stan 05-123. Briefly, companies under contract for design functions for the UK MoD have their company structure and key personnel assessed for the acceptable level of design competence for the scope of the specific contract. The assessment is carried out by the Integrated Project Team responsible for placing the contract assisted by ADRP staff. If the company is acceptable they are then put on the register of Approved MoD Companies. If the company has a change of personnel, location or management structure it will need re-assessing. Inclusion in this scheme is not an essential pre-requisite for the award of design and development contracts, however an assessment of the company will normally be carried out by the IPT assisted by ADRP.

RESTRUCTURING OF DEFENCE STANDARD 00-970

Design, Airworthiness and Operational procedures for military aircraft are produced by the MoD. Considerable work has already been done to revise and produce a set of Design Requirement for aircraft and UAV Systems. Def Stan 00-970 (Design and Airworthiness Requirements for Service Aircraft) has grown in size and complexity since its conception and at present comprises two volumes each of three books covering respectively fixed and rotary wing aircraft. It is now under going revision, the aim being to eliminate duplication and irrelevant material and to present the document in a modular format with the information being presented in a more structured manner. The first tranche of work will be published this year (1999).

New Format of DS00-970

Part 0 - Guidance and definitions
Part 1 - Combat Aircraft (A/C)
Part 3 - Small Civil Type A/C
Part 5 - Large Civil Type A/C
Part 7 - Rotorcraft
Part 9 - UAV Systems (was Def Stan 05-127)
Part 11 - Engines (was Def Stan 00-971)
Part 13 - Military Common Fit Equipment
- **Includes:**
- **NVG Compatibility**
- **Recce Pods**
- **Electrical Installations**
- **Aircrew Equipment Assembly**
- **Launchers**
- **Role Equipment e.g. Aero Med.**
- **TRD (Towed Radar Decoys)**

Part 15 - Items With No Military Specific Requirement
- **Auxiliary Power Unit (APU)**

Propellers
Very Light Aircraft (VLA)
Gliders
Airships

DS 00-970, will be published in nine Parts. It will be issued in CD ROM (hypertext linked) or "Hard Copy", but the idea is that in the future it could be published on the Internet with linked access to all other Standard references. You will note that only the odd numbers have been allocated this to ensure that any additional new requirement, such as for example, future Spacecraft can be inserted.

DEF STAN 00-970 PART 9 - DESIGN AND AIRWORTHINESS REQUIREMENTS FOR UAV SYSTEMS

In the late 1980's it was agreed between Industry and MoD, that there was a need to produce a Defence Standard which would cover elements of unmanned and manned aircraft. A new Defence Standard was drafted. While at the same time SBAC/MoD set up a joint working group to produce a "Guide To The Procurement, Design And Operations Of UAV Systems", however, neither of these documents had sufficient depth. In 1992 MoD decided to produce a more detailed Defence Standard and formed a Sub Committee under the Joint Technical Requirements Committee (responsible for Weapon Systems Design Standard). The sub-committee reviewed the two documents and started producing new draft material as well as extracting relevant information from the previous publications to form the new standard.

In 1996 reorganisation of ADRP took place, this resulted in responsibility for the sub committee being passed to the aircraft side under the Joint Airworthiness Committee and the sub -committee was renamed the Unmanned Air Vehicle Systems Sub-Committee (UAVSSC). At this point a decision was made to place the design requirements into Def Stan 00-970. The present Committee Chaired by ADRP2, has members from MoD, CAA, SBAC and other aircraft related Industries. The committee, discusses, drafts and prepare papers to be ratified by the JAC. The committees terms of reference are:

UAVSSC - TOR

- **Establish and prepare new Part 9 covering design and airworthiness requirements for UAVS.**
- **Examine current standards to determine their applicability to UAVS**
- **Recommend insertion of design and procedural clauses into other related Defence standards.**
- **Consider any document generated by other organisations relating to UAVS, which had material relevant for incorporation into the new standard.**
- **Draft paper for submission to the JAC**
- **To advise the JAC and other sub-committees on UAV matters.**
- **Act as a forum to advise UK representative on NATO and other related committees.**
- **To provide advice and comment on draft standards by NATO, BSI, CAA and other organisations.**
- **To maintain an awareness of UAV matters in other areas and countries**
- **Ensure there is no duplication of effort between The UAVSSC and other MoD committees.**

Initially this committee was only concerned with UAV's flown over MoD ranges, and the documentation produced reflected that fact. The possibility of flying "off range" was not even considered. The effective use of UAVS during Desert Storm and later Bosnia has brought about a reversal of thinking and in 1996 the focus of the document was expanded to encompass both targets and reconnaissance and surveillance mode UAVs, that could have off range applications. Clearly to be able to fly off range any UAV system must demonstrate, that the system is safe and reliable. A formal design certificate must then be issued by the contractor with all supporting documentation so that the MoD Integrated Project Team Leader (IPT/L) can be satisfied that the system is viable and can issue the MA Release.

Once in Service, the MoD IPT/L is responsible for monitoring the configuration control of the system to ensure that the design and agreed operating procedures always meet the required standard of airworthiness and safety.

If we look at the Criteria for UAV Safety, the aim is that it should be no less safe then other military aircraft. The probability that the operation of the system would cause serious injury or fatality to personnel or the general public due to catastrophic technical failure, should be in the order of 1×10^{-6} per flying hour during normal peace time operations. Risk reduction techniques can be considered and put into force if the UAV is to be operated in a controlled environment such as on a range. This can be achieved by operating procedures and by having installed other risk reducing systems such as; flight termination or a limited flight fuel load.

Safety Assessment of the system should take into account the following factors:

The Safety Assessment covers Reliability of the:
Structure.

Engine.
Avionics.
Command and Control System and Links.
Software.
Flight Termination System.
Mode of Operation.
Risk of collision with other aircraft.
Population density and exposure time over area over flown.
Risk reduction techniques and procedures implemented.
Political situations such as tension, Threat, TTW.

Operational need and advances in technology and miniaturisation of components, coupled with improved reliability of components mean that off range flying of UAV Systems is being considered in the United Kingdom. This expansion of capability gives rise to increasing challenges in establishing a satisfactory level of airworthiness. It is with this in mind that the JAC are producing Part 9 of the Defence Standard on Design and Airworthiness Requirements for UAV Systems.

Defence Standard 00-970 Part 9 will be a living document, the intention is that it should identify the minimum standard of airworthiness and safety which will give the required system integrity for any UAV Design. It will form the initial building blocks for the more sophisticated future systems vehicles.

Part 9 of the Defence Standard is divided into five Sections, they are:

Sect 1	**General Requirements**
Sect 2	**System Characteristics**
Sect 3	**Support Facilities/Control Station**
Sect 4	**Air Vehicle**
Sect 5	**Design Qualification**

We will now look at each section, in more detail:

Section 1 General Requirements

Clause 1.1	Introduction and Purpose
Clause 1.2	Applicability and Scope
Clause 1.3	Definitions
Clause 1.4	Referenced Documents
Clause 1.5	Operational colouring and Marking
Clause 1.6	General Operational Environmental Conditions

Section 2 System Characteristics

Clause 2.1	Reliability and Maintainability
Clause 2.2	Hazard Analysis and Safety
Clause 2.3	Software
Clause 2.4	System Environmental Requirements
Clause 2.5	EMC
Clause 2.6	ECCM
Clause 2.7	Electronics
Clause 2.8	Range Interfacing
Clause 2.9	Guidance on Design and Assembly

Section 3 Support Facilities (Control Station)

Clause 3.1	General
Clause 3.2	Specific Climatic Conditions
Clause 3.3	Launch and Retrieval
Clause 3.4	Ground Control
Clause 3.5	Maintenance

Section 4 - Air Vehicle

Clause 4.1	General
Clause 4.2	Specific Climatic Conditions
Clause 4.3	Flight Performance
Clause 4.4	Structural Strength Requirements
Clause 4.5	Airframe
Clause 4.6	Power Plant
Clause 4.7	Avionics
Clause 4.8	Flight Termination
Clause 4.9	Payloads
Clause 4.10	Electrical Systems and Wiring

Section 5 Design Qualification

Clause 5.1	General Principles of Design Qualification

Covers the requirement for:

a. Environmental Testing
b. Compatibility Testing
c. Structural Validation
d. Performance Modelling
e. Performance Testing
f. Safety Testing
g. Reliability
h. Flight Test Requirements
j. Demonstration of behaviour on System Failure
k Performance Testing of Data Link for:
Flight Termination
Controllability on the Ground
Launch Take Off and Climb
Recovery, Approach, Landing and Overshoot
Longitudinal Stability and Control
Lateral and Directional Stability and Control
Rapid Roll/Roll coupling

l. Demonstration Limits of Flight Envelope
m. Launch System
n. Testing of Ground Control System
o. Controllability on the Ground
p. Launch Take Off and Climb
q. Recovery, Approach, Landing and Overshoot
r. Handling and Performance in Icing

Conditions
s. Testing of Launch System

Each Clause follows the JAR format, however the presentation is set out as a table with the format in landscape. The **Requirements**, **Compliance** and **Advisory** material for each Clause or sub-Clause are set out on the same page.**(See Figure 3, a representative page from Section 4 of the document).**

The new format contains:

- **Requirements - These are mandatory**
- **Compliance - The suggested means of achieving the requirement which can be mandatory**
-
- **Guidance - Identifies the risk, the requirement addresses plus other salient information**

If we look at the philosophy behind the standard, it has been written to put the responsibility for design, on the designer and not the procurer. In this way it eliminates the constraints previously applied and allows for innovative designs to be considered as long as it can be proven that safety is not degraded. To do this is a clear audit trail is required using the information in related Defence Standards such as:

00-35- Environmental Handbook for Defence Material
00-38 Guidelines for the Evaluation of Micro-processors for avionic application
00-40
00-41 } Reliability and Maintainability
00-44
00-55 Safety Related Software
00-56 Safety Management of Defence Equipment
00-970 Design and Airworthiness Requirements for Service Aircraft

FUTURE DESIGN AND OPERATING CONSIDERATIONS.

Highly manoeuvrable high G capability thrust vectored UAV's are only a short time away. Their high acceleration and manoeuvrability will mean that the human operators reaction times will be too slow, and fully autonomous operation will be required. To achieve the necessary airworthiness and safety, high integrity hardware and software will be required. The failure of the UAV to perform its functions correctly will have, as well as operational, environmental and financial implications, the possibility of causing multiple deaths and/or injury to innocent bystanders. If loss of life is a possibility, the system can be considered to be **SAFETY CRITICAL.** A Hazard Analysis should carried out To assess the risk of system failure which could lead to an **Accident**.

Accident:
Event that causes death, injury or damage to equipment.

Hazard:
Situations with potential for causing an accident

The procedure above will not alter if operating micro UAV's. Headlines like:

"BOY KILLED BY MODEL AIRCRAFT AT AIR SHOW" (in a recent newspaper)

do not help when trying to get approval to fly military or commercial UAV Systems. Designers and operators must be aware that any UAV even those weighing 20kg and below still has the potential to cause death, injury or damage and requires therefore a **Safety Assessment** to be carried out and a **Safety Case** and **Hazard Analysis** to be submitted for approval.

CONCLUSIONS

This presentation has been concerned with the factors which affect development of design requirements for operation of UAVS by the UK MoD. It has also provide a brief summary of how the MoD, regulate airworthiness and safety through a series of procedures and Defence Standards. UAVs are a growth industry, with great potential Several systems are already being considered for civil and military operations and are only being delayed because of airspace issues, it is therefore essential that safety and airworthiness are part of the design process from concept, through life to disposal (cradle to grave).

End

DASB/JAC COMMITTEE STRUCTURE

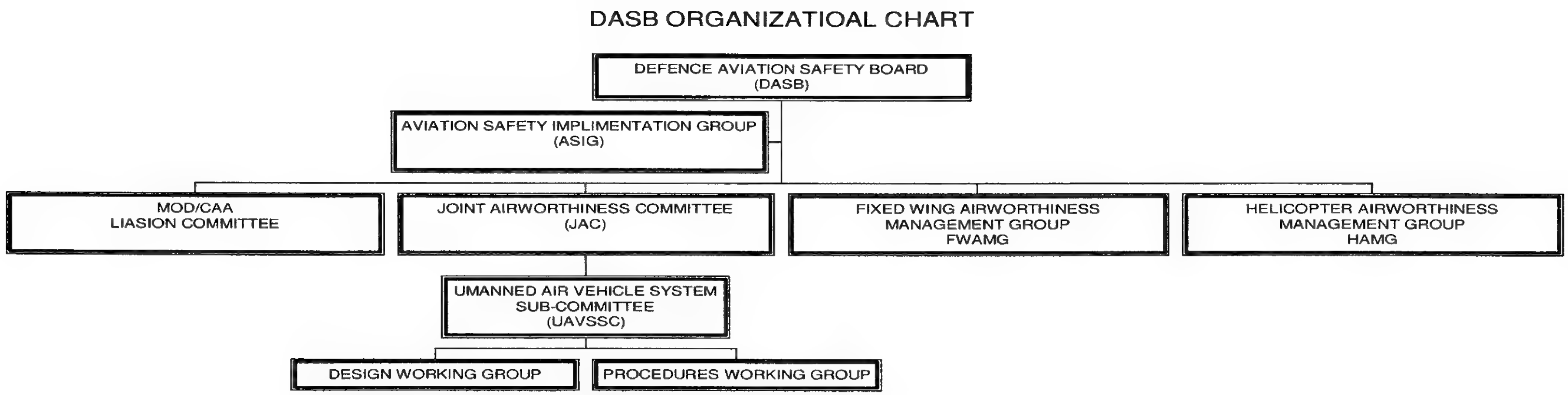

Fig 1

ADRP FAMILY TREE

(17 August 1999)

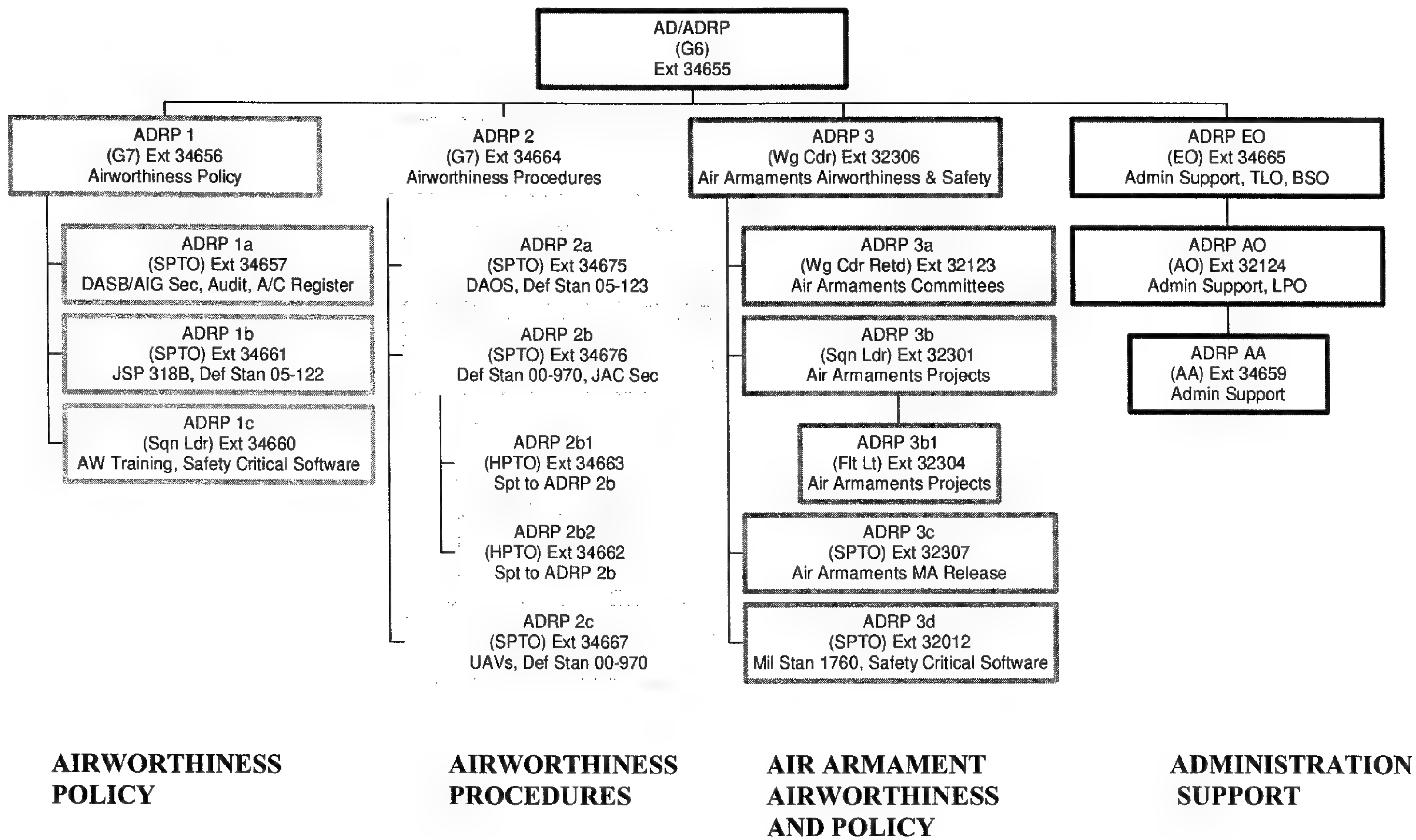

Fig 2

4.3 FLIGHT PERFORMANCE

REQUIREMENT	COMPLIANCE	GUIDANCE
4.3.2 DESIGN PROCESS		
a. The flight performance shall be achieved using proven or acceptable design procedures.	The design of the UAV and all related systems which directly affect flight performance shall be supported by a full Engineering Record, with reference to all source documentation, to ensure traceability. All analytical design processes, and other material generated in the design of each system element, shall be countersigned by an agreed list of approved signatories.	Proven or acceptable design procedures are those that either: (1) have a recognised precedent with a proven record of reliability and integrity, and are supported by accepted technical documentation such as data sheets or theoretical/analytical procedures, or (2) may otherwise be shown to have the required integrity by other methods deemed to be acceptable to the Project Director.
b. The flight performance and flying characteristics shall not be unacceptably degraded by tolerances associated with the design, manufacture and assembly processes, or by variability in component/sub-system performance.	Consideration shall be given to the cumulative effect of all such tolerances, when applied in a wholly adverse or asymmetric way. This effect shall be quantified by prediction methods, or test.	Variability in the performance of systems, sub-systems or individual components can further arise throughout their service life by environmental and operational factors such as storage conditions, ageing, wear & tear, repair and exposure to moisture or sunlight.
c. The design of the UAV shall ensure that flight performance is not unacceptably degraded by equipment which is temporarily carried by the UAV for a specific purpose, and which is either jettisoned, or otherwise changes the configuration of the vehicle.	Performance degradation shall be predicted by analysis of the drag and mass properties of the equipment concerned, and simulation of its effect upon the predicted performance of the basic UAV	All supplementary equipment, particularly that carried externally, should be of an equivalent aeronautical standard of design, manufacture and reliability to that of the UAV.
d. The design shall take into consideration the mass properties of the UAV in order to ensure that flight performance requirements are met.	UAV mass properties shall be estimated by either numerical methods or direct measurement using an accurate mass model for each relevant build standard or flight configuration. Where possible the data should be verified and validated by measurement using actual vehicles.	UAV mass properties have potentially wide-ranging implications on factors such as flight performance, control and handling characteristics, structural loading, launch/ recovery characteristics and operating danger areas (safety trace calculations).

Fig 3

ENVIRONMENT

		MILITARY	CIVIL AIRSPACE			
		NOTIFIED AIRSPACE	UNCONTROLLED	CONTROLLED		
WEIGHT	ABOVE 300Kg	B	B	A	HIGH	**POPULATION DENSITY**
	20-300Kg	C	B	A	MEDIUM	
	BELOW 20Kg	C	B	B	LOW	
		TRAINING	MIXED FLEET & TTW OPS	MIXED FLEET & PEACE-TIME OPS		

OPERATIONAL REQUIREMENT

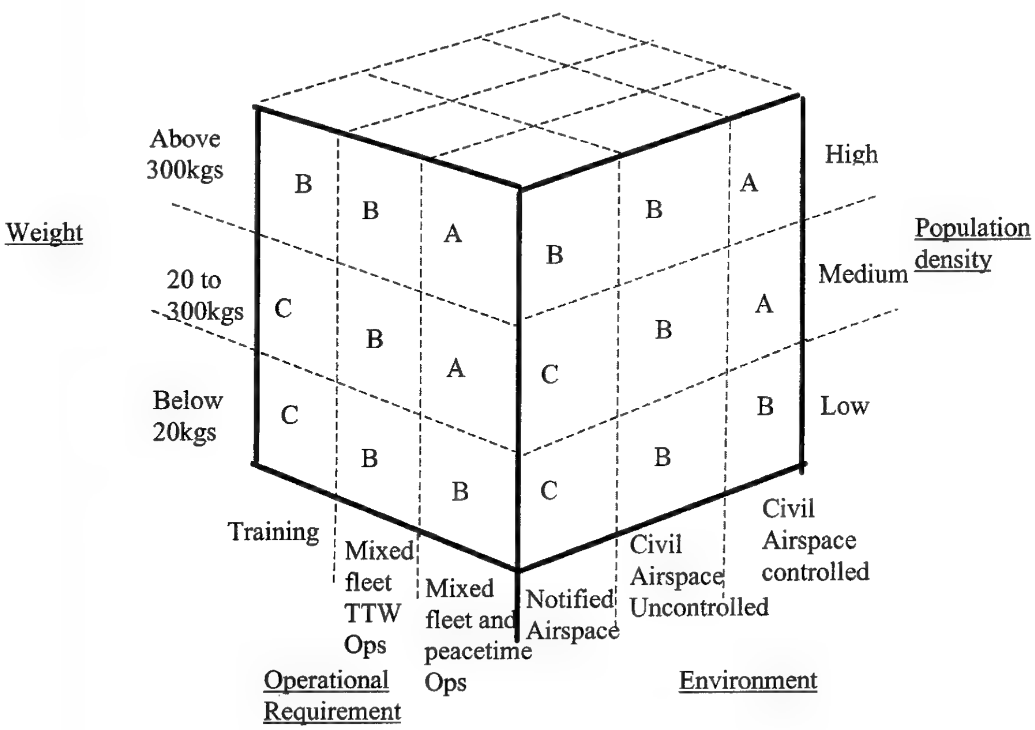

Fig 4

UAV Data-Links: Tasks, Types, Technologies and Examples

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Introduction

This paper provides an overview of Data-Links for UAVs. Based on the functions, which have to be performed in different UAV missions, requirements for data-links are identified.

After highlighting the basic variants of data-links and their general advantages and disadvantages a detailed discussion of some important design aspects is provided.

Some real-world examples of data-links show how theory has been put to use, namely

- Global Hawk SATCOM Data-Link as an example for an off-the-shelf solution.
- HF Data-Link for Mücke UAV System as an example for the adaptation of MOTS hardware to a small UAV.
- The BREVEL Microwave DATA-Link as an example for a solution to a specific requirement. The BREVEL Data-Link is one of the most advanced solutions available today. It was developed jointly between DaimlerChrysler Aerospace AG and MATRA SYSTEMS & Information until 1998 and is expected to go into production in Germany in 1999.

DaimlerChrysler Aerospace (Dasa) History on Data-Links (viewgraphs 2 to 4)

Data-Link activities in Dasa have started in the former AEG company in Ulm, which was later-on merged with Dornier, Messerschmitt-Bölkow-Blohm, MTU and others to form Daimler-Benz Aerospace (now DaimlerChrysler Aerospace, Dasa) which now also comprises the former Defense Activities of SIEMENS. With revenues of 17 Billion DM, Dasa makes up about 7 % of the business in the DaimlerChrysler Group. Data-Link activities of Dasa are handled within the Defense and Civil Systems Division, which has its premises in Ulm, Munich and Friedrichshafen.
Data-Link Activities for missile and UAV systems started in the 1970s with the command link for the ROLAND Air Defense Missile System.
Currently numerous data-link activities are in the feasibility or DemVal phase. Dasa Ulm (VMFW3) was the leader of a co-operation with MATRA Systems & Information for development of the Microwave data-link for the BREVEL UAV system. An HF data-link based largely on MOTS hardware is currently in development in Ulm for the German Mücke Jamming UAV System.

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.

UAV DATA-LINK TASKS AND REQUIREMENTS

(viewgraphs 5 to 9)

Unmanned Air Vehicles have enjoyed growing importance during the last two decades.
UAV Systems today are used to perform a multitude of missions both military and civilian. Typical UAV missions in the military field comprise

- Reconnaissance
- Targeting and Fire Control
- Attack
- Suppression of Enemy Air Defence (SEAD)
- COMINT and ELINT
- Jamming

Many of these missions require instantaneous exchange of information between the UAV and a ground-control station. This information exchange is performed by a DATA-LINK.

Depending on the particular mission one or more of the following functions have to be performed, which involve a data-link.

- The flight-path of the UAV has to be controlled from the ground, the platform of an on-board Sensor is to be directed, or an on-board equipment, e.g. a jammer, has to be activated or de-activated. All of these actions require a communications channel from the ground to the UAV.
  This channel is called TELECOMMAND UPLINK (TC) and can usually be of low capacity.
- The status of the UAV itself or of an on-board equipment has to be monitored in the ground control station. Information from on-board sensors, which only deliver a limited amount of data, e.g. altimeter or inertial measurement unit, may also have to be transferred.
  These data from the UAV to ground can be transmitted through a low capacity channel, which we call TELEMETRY DOWNLINK (TM).
- In missions like surveillance or target search, fire control or battle damage assessment a large amount of data from on-board SAR radars or electro-optic sensors has to be transmitted from the UAV to a ground control station. This amount of data requires a channel with very high data rate. This channel is called TELEVISION DOWNLINK (TV).
- In case of UAV missions, which are concerned with fire-control of weapon-systems, ground-targets have to be located by the UAV with a precision, that is compatible with CEP or footprint of the weapon. Consequently the location of the UAV has to be known with of least the same precision. Although this is principally possible with GPS using the military P/Y code, jamming of GPS in a tactical UAV is relatively easy in a battlefield scenario. It is especially likely if the enemy knows that the UAV presents a high threat. Therefore this localization function should be integrated into the data-link if sufficient accuracy can be achieved.

Data-Link Range, depending on UAV class and task can be from 20 km to several hundred kilome-ters. Data rates can vary from around 100 bit/s for control data to over 100 Mbit/s for uncompressed video.
Data-Links employ communication modes of different complexity:

- Simplex, so that the sender has no knowledge of correct reception of his transmission
- semi-duplex, allowing confirmation of small packets so that errors can be corrected with minimum delay
- full duplex, which puts both sides in continuos communication with each other and allows a maximum degree of error-free information transfer and thus reliability.

The type of link mode also determines to a large extent the degree of ECM susceptibility, which is of importance for military 'UAV missions.

Data-Link equipment has to be suited to the space and environmental conditions found in the UAV and must not interfere with other systems onboard the UAV.
For tactical UAVs the data-link equipment must normally not exceed 20 kg in mass and 200 W of power consumption. Less is always preferred.
Data-Link equipment in the ground station, depending on the type of UAV system may be subject to the same or even more demanding conditions, than in the UAV. This is especially true for tactical UAV systems, which require a highly mobile ground station.

In addition to the environmental conditions for the Air Data Terminal and the Ground Data Terminal there are also environmental conditions for the communications channel itself.

Depending on frequency range the commu-nications channel features self implied charac-teristics like

- Line of sight conditions
- Attenuation imposed by range, atmosphere and weather
- Disturbances like multipath effects, noise and
- Ionospheric disturbances and daily variations resulting from solar activity.

In addition to these natural influences, the communications channel is subject to intentional influences by various types of jammers like

- noise jammers, both wide and narrow band
- pulse jammers
- spot jammers
- repeater jammers and
- intelligent jammers.

A low probability of intercept of the data-link reduces the risk of jamming.

These effects of the communications channel have to be taken into account in data-link design based on the requirements and criticity of the UAV mission.

UAV DATA-LINK TYPES AND GENERAL CHARACTERISTICS

(viewgraphs 10 to 17)

From the users point of view the main selection criteria/requirements are usually

- Range and
- Data-Rate.

In addition to that

- Link Protection (Jamming Resistance)

is an important requirement.

When looked at by the designer, these requirements have to be translated into

- operating frequency
- bandwidth
- antenna characteristics
- signal processing.

These criteria are used in this chapter to identify some basic data-link variants and to characterize them by their main characteristics.

Analog Versus Digital (viewgraph 11)

A powerful reservoir of signal processing techniques is available to the designer to provide a high degree of link protection. These techniques will be dealt with in more detail in the next chapter.

For the purpose of general classification in this chapter it is of importance that most of these signal processing techniques require a **digital** data-link as compared to an **analog** one.

While in an analog link signal are transmitted by traditional modulation techniques such as

- amplitude modulation (AM Radio)
- frequency modulation (FM Radio)

which transform all characteristics of the original signal into the RF wave form, a digital link takes a different approach. The original signal is first digitized; the resulting data stream is used to modulate the carrier by means of

- Phase Shift Keying (PSK) or
- Frequency Shift Keying (FSK)
- Amplitude Shift Keying (ASK).

Thus the RF signal only varies between two conditions at any time.

A digital link allows to manipulate the signal in order to create redundancy and jam resistance to a much larger extent than possible in an analog link. While analog links are still widely used in UAV systems today digital links are clearly going to become the future standard.

Bandwidth (viewgraph 12)

Bandwidth is the resource, which is required to transfer a certain amount of information in a given time-segment. In addition most of the signal-processing techniques used in digital links in order to provide jamming resistance are bandwidth-consumers on top.

In image- and TV-transmission, compression techniques can be applied to the signal from the camera to limit the amount of information and thus the bandwidth requirement. MPEG and JPEG are common compression techniques used in computing devices for the consumer market.

Generally speaking, the data-rate of a digital-link using BPSK (expressed in bit/s) is roughly identical to the required bandwidth (expressed in Hz).

In a radio frequency system, many components, e.g. antennas and amplifiers, can only cover a certain

percentage of their operating frequency before their performance deteriorates substantially. For this reason the usable bandwidth can generally not exceed ~ 3 % of the operating frequency.

Operating Frequency (viewgraph 13)

When selecting the operating frequency of a data link the following aspects have to be taken into account

- propagation characteristics
- achievable power
- achievable antenna characteristics
- available bandwidth.

The frequency spectrum from HF to microwave can generally be characterized as follows:

- HF frequencies (1-30 MHz) propagate by ground-wave, sky-wave and line-of-sight and thus allow coverage of long distances.

  However, usable bandwidth is small and antennas with gain are gigantic in terms of UAV dimensions.

- VHF/UHF frequencies (30 MHz to 1 GHz) can cover substantial distances through propagation by diffraction in the lower part of the spectrum.

  However, power levels for diffraction propagation are too high to be feasible in small UAVs and antennas with gain are still too big.

- The Microwave Spectrum (1 GHz to 100 GHz) is of main interest to UAV applications, as it offers the possibility to use high bandwidth for picture transmission. Antennas of high gain can be built at dimensions, which can be accommodated in a UAV.

  The drawback of the microwave spectrum is that propagation is limited to line-of-sight and power levels are limited to a few watts unless high voltage tube transmitters are used.

Based on the above the general characteristics for three basic variants of UAV links are described.

Short-Wave (HF) Data-Links (viewgraph 14)

Due to sky-wave propagation by reflection at the earth's ionosphere short-wave links can cover up to about 500 km (non-line-of-sight) at power levels and antenna sizes feasible in a UAV installation.

Due to bandwidth limitations to ~ 100 kHz HF data-links can generally not be used for TV picture transmission. An exception is the transfer of still (frozen) TV images, which can be transmitted by so-called slow-scan techniques (1 picture typically takes more than 10 seconds). Due to variations in propagation characteristics the usable part of the HF spectrum for UAVs is limited to the range of 2-12 MHz.

Microwave Data-Links (viewgraph 15)

Microwave Data-Links are clearly the workhorse in UAV applications. They are characterized by benefits like

- large available bandwidth which allows transmission of live-video.
  The following bands are used for to data-link applications
  - Ku-Band (15 GHz)
  - X-Band (10 GHz)
  - C-Band (5 GHz)
  - L-/S-Band (1-2 GHz)
- High Bandwidth together with high gain antennas, which can be installed in UAVs due to their relatively small dimensions, allow to make microwave links jam-resistant.

The only disadvantage in microwave links is that they depend on line-of-sight propagation, which limits their coverage to < 100 to 300 km depending on UAV altitude and terrain.

If the UAV mission cannot tolerate this limitation an airborne relays has to be used. This can either be an aircraft, another UAV or a satellite.

Satellite Data-Links (viewgraph 16)

Satellite Data-Links are a special case of a microwave data-link to overcome the range limitation normally imposed by the line-of-sight requirement.

Depending on the number and orbit of the satellites used satellite links can give a UAV world-wide coverage.

Limitations for the use of satellite links are

- Availability of military communication satellites
- Cost and availability of commercial wide-band satellite capacity
- The long distance of the UAV to satellite requires extremely high-gain directional antennas, which cannot be installed in tactical small UAVs.

The use of wide-band satellite data-links today is mainly limited to High-Altitude, Long-Endurance (HALE) UAVs in countries, which can secure satellite transmission capacity.

For tactical UAVs satellite links are not (yet) an alternative today.

UAV DATA-LINK DESIGN ASPECTS AND TECHNIQUES

(viewgraphs 17 to 39)

The key factors in data-link design are the requirements concerning

- Jamming-Resistance
- Range
- Data-Rate

In today's battlefield environment Jamming-Resistance and Low-Probability-of-Intercept of the data-link are extremely important factors for mission success.

These requirements have to be fulfilled under the constraints imposed by the Air Vehicle, which are mostly more stringent than the constraints to the Ground Data Terminal.

Constraints for Air-Vehicle Integration (viewgraph 18)

The air-vehicle imposes limitations to the airborne data link terminal in terms of :

- weight,
- size,
- power supply,
- thermal dissipation,
- antenna.

These limitations influence some key design features of the data link like:

- **Transmitter power** is limited by power-supply of the A/V, allowable thermal dissipation, mass and size.
- **Antenna type and gain** are limited by the antenna mass, size and position, which is allowed by the A/V under aerodynamic considerations.
- **Frequency band** has to be chosen based on the antenna size and transmitter-power, which allows to satisfy the link budget under jamming conditions.

Link Budget

The link budget is the output of the link analysis. It consists of the calculations and tabulation of the useful signal power and the interfering noise power available at the receiver.

Link Protection and Quality

In the case of military applications, one of the specific constraints is to provide the quality required for the communication under threat, generally in the presence of hostile jamming, which represents also additional sources of noise in the link.

Typical protection methods are :

- directional antennas,
- robustness of the modulation
- spread spectrum techniques
- forward error correction.

The above design considerations will finally lead to certain degrees of complexity, flexibility and cost, which together with the data-link performances have to be subject to trade-offs to come to a well-balanced, optimized and cost-effective solution.

Definition of Link Quality and Link Budget Examples

(viewgraphs 19 to 27)

Quality of a communications link in general terms is determined by

- Radiated power from the transmitter and the
- Minimum signal power at the receiver, required for communication.

In these terms link quality is the maximum allowable path loss between transmitter and receiver if jamming and other interference is not considered.

The major tool for analysis of link quality is the link budget.

The link budget is a balance of gains and losses, e.g.

- transmitter power (on board power is limited)
- antenna gain (size is limited by UAV shape and aerodynamics)
- processing gain

- propagation losses due to atmospheric attenuation and earth surface effects depending on frequency band (UAV mission area)
- Losses due to real-life imperfections in the signal amplification and processing circuit.
- engineering implementation inside the UAV.

Radiated power P_0 from the transmitter expressed in dBm leads to a decreasing power density p depending on the distance d to the receiver. In free space this power density can be expressed as

$$p = \frac{P_o}{4\pi d^2}$$

From the capture area (aperture) of the receiving antenna (A) and wavelength (λ) the receivers antenna gain G in dB can be calculated as

$$G = 10 \log \left(\frac{4\pi A}{\lambda^2} \right)$$

The received signal power S expressed in dB above 1 mW (dBm)is thus

$$S = P_0 + G - 10 \log \left(\frac{4\pi d}{\lambda} \right)^2 .$$

This received signal power has to compete with self-generated thermal noise in the receiver, which results from molecular movement in the receivers components. This noise is bandwidth dependent, so that it is more significant for signals with high data-rate r.

The noise power N in dBm can be calculated as

$$N = -174\, dBm + 10 \log (r) .$$

The result of S and N is the so-called signal to noise ratio (SNR)

$$\mathrm{SNR} = \mathrm{P_0} + \mathrm{G} - 10 \log \left(\frac{4\pi d}{\lambda} \right)^2 + 174\ \mathrm{dBm} - 10 \log (\mathrm{r}).$$

The Signal to Noise Ratio allows an initial rough judgement of data-link performance.

For standard modulation techniques an SNR of ~ 10 dB will allow error free communication. Special modulation techniques allow communication at considerably lower SNRs.

However, with this initial SNR calculation one has to keep in mind that losses from

- cables, radomes, switches
- weather
- multipath effects and
- jamming

have to be taken into account additionally.

On HF the thermal noise generated in the receiver is generally of no significance. The limiting factor here is atmospheric noise, which depends on time of day and frequency (viewgraph 23).

Some examples of path losses in typical microwave bands show that the additional path loss at high frequencies (e.g. 15 GHz) when compared to low microwave frequencies (e.g. 2 GHz) is more than compensated by the antenna gains in the UAV at 15 GHz. This gain at 15 GHz has the added advantage that it comes along with a narrow beam-width < 10°, which can be put to use for anti-jamming purposes. These narrow beam antennas on the other hand result in some additional complexity for antenna control as the antenna has to remain pointed to the ground station during all UAV manoeuvres (viewgraph 24).

From a simple example of a link budget for a TV data-link in Ku-band it can be seen, that the antenna gains, which are possible at this frequency, allow communication over a distance of 100 km in adverse weather with a transmitter power of less than 1 watt.

The corresponding power for omni-directional antennas would be 1.2 MW (1,2000,000 W) instead. Transmitters of this power level are neither feasible in Ku-band nor could they be packaged in an airborne platform (viewgraph 25).

Although significant distances can be covered at microwave frequencies from a link budget point of view it has to be always kept in mind that the line of sight condition has to be satisfied in the first place. Although ranges of 180 km can be covered with UAV altitudes of as low as 1500 m even slightly hilly terrain can reduce this range to less than 100 km at the same flight altitude (viewgraphs 26, 27).

Jamming Resistance (viewgraph 28)

In addition to propagation effects, jamming is another important influence on data-link quality.

In today's battlefield environment jamming-Resistance and Low-Probability of Intercept of the data-link are extremely important factors in UAV missions success.

In a jamming environment the transmitted signal may well have to compete with jamming-signals, which are 10.000 times or 40 dB stronger.

Some anti-jamming features will be looked at in more detail in the following:

- Narrow Beam Antennas
- Direct Sequence Spread Spectrum
- Frequency Hopping Spread Spectrum
- Channel Coding.

Narrow Beam Antennas (viewgraphs 29 to 31)

Jammers, which do not enter directly into the main lobe of the antenna, can be attenuated substantially. When received via sidelobes jammers are attenuated by ca. 20 dB for the first sidelobe and by an even greater amount for the far side-lobes. Antennas designed for particularly low side-lobes reach an attenuation of > 40 dB for the far side-lobes. Thus the areas, which can be protected by a jammer, can be reduced substantially.

Generally the wide-band TV channel from the UAV to ground is the most vulnerable part of the link; consequently the Ground Data Terminal should be equipped with the narrowest antennas in order to make the receiver as jamming-proof as possible.

For a given size of the antenna the highest frequency band will allow the narrowest antenna beam.

For a given transmit power and volume in ADT and GDT the gain and sidelobe suppression advantage of Ku-Band antennas over S-Band antennas will result in a jam-resistant Ku-Band range up to 100 km while S-Band and C-Band communication are totally lost and X-Band range is reduced to 50 km.

Signal Processing for Anti-Jamming (viewgraph 32)

A typical digital data-link can be designed for anti-jamming performance in the following way: After Channel-Coding of the source data stream, the coded data stream is multiplied by a higher rate spreading code. The resulting high-rate data stream is used to modulate an intermediate-frequency microwave signal by a digital modula-tion, e.g. BPSK. This results in a so-called Direct-Sequence Spread Spectrum Signal at the interme-diate frequency, which is mixed to a set of trans-mitting frequencies in the band of operation by means of a Frequency Hopping Synthesizer which selects one of the frequencies at a time.

The different steps of signal processing shall now be looked at in a bit more detail below.

Channel Coding (viewgraphs 33, 34)

This technique serves the purpose of structuring the data stream and adding redundancy, which allows to

- identify corrupted parts of the message after reception
- correct the errors by making use of the redundancy introduced in the transmitted data stream.

A special feature in channel coding is the interleaving of information. By this technique a block of the transmitted signal, which can be corrupted e.g. by a pulse jammer, is transformed into many small parts of words in the coded data stream. These small parts, when corrupted, can still be detected and corrected by the outer coding.

Direct Sequence Spread Spectrum (viewgraphs 35 to 37)

Another efficient way to minimise interference by jamming signals is to spread the power spectrum of the signal before transmission and to de-spread it after reception. This leads to the effect, that the bandwidth of the transmission is much larger than the minimum bandwidth, which would normally be required.

In DSSS each Bit of the original Signal is multiplied with a specific DS Code. This leads to a pseudo-random DSSS Signal, which is used to modulate the Radio Frequency Signal by BPSK (Phase Shift Modulation). After reception and demodulation the signal is correlated with the same DSSS Code used in the transmitter. Unless a jammer has knowledge of the DS code and thus uses exactly the same waveform and synchronization (which is very unlikely) it is substantially attenuated by DSSS. The same is true for unintentional interference effects in the communications channel.
The DSSS code can be selected from a data base of codes and loaded into the data-link equipment prior to the mission. The probability of a jammer using the data-link DSSS code is therefore mini-mal.

Frequency Hopping Spread Spectrum (viewgraph 38)

In the case of an extremely strong Noise Jammer further anti-jamming features are useful in addition to DSSS. By Frequency Hopping Spread Spectrum (FHSS) the carrier frequency of the transmitter

signal is changed pseudo-randomly according to the FHSS code between a given number of frequencies.
By FHSS the effectiveness of a jammer, which can overcome DSSS is reduced proportionally to the number of frequencies used, so that the remaining interference effects can be corrected by channel-coding.
As for the DSSS code the FHSS code can be selected from a database and loaded into the data-link equipment prior to the mission.

Data Link Design Summary (viewgraph 39)

As a consequence of the previous discussions the following design features should be selected for a wide band microwave data-link.

- Use of Ku-Band

  In addition to the fact that this band is recommended for UAV use by NATO the Ku-Band has the following advantages

  - allows very small antennas at sizes, which can still be accommodated in a tactical UAV
  - a wide frequency range is allocated for data-links, which allows very wide-band transmission. Very high bandwidth together with frequency hopping and direct sequence spread spectrum is very difficult to implement in the other microwave bands due to congestion.

- Directional antennas should be used to limit transmitter power and to make the link jam-resistant and difficult to intercept. Additionally narrow-beam antennas can reduce multi-path effects and allow angle-tracking of the UAV.

- Direct Sequence Spread Spectrum (DSSS) improves the jamming resistance of the link and allows a precise measurement of the distance to the UAV.

- Frequency Hopping Spread Spectrum further improves the links jamming resistance and is a very effective way to minimize the influence of multi-path effects.

- Channel Coding allows to minimize the Bit Error Rate (BER) for a given signal to noise ratio and allows to correct errors. Interleaving is an effective counter-measure against pulse jammers.

UAV DATA-LINK EXAMPLES

UAV Satellite Link – Example: Global Hawk (viewgraphs 41, 42)

Global Hawk is a high-altitude, long endurance UAV equipped with SAR and EO sensors. With a range of ca. 25,000, a maximum altitude of 20,000 m and a mission time of up to 40 h it is a truly impressive UAV.

The UAV has a size, which comes close to manned aircraft of the business-jet class. This size allows some flexibility in the selection of on-board equipment.

As a result military off-the-shelf (MOTS) equipment could to be used for the SATCOM Data-Link. By combining a number of standard 1.5 MBit/s SATCOM channels an overall data-rate in excess of 45 MBit/s can be achieved.

This size of aircraft allows to accommodate the very sizeable antenna, which is necessary for this type of SATCOM Link. With an antenna diameter of 1.25 m and a volume of ca. 1 m^3 the space taken up by the antenna unit would be sufficient to accommodate a complete tactical UAV.

To keep the pencil beam of this antenna (~ 1.5°) focussed on the satellite high precision antenna control and a very accurate long term measurement of the UAV's orientation in space are necessary.

In a UAV of this class the choice of SATCOM is a feasible way to avoid many of the problems that tactical UAVs are facing.

HF UAV Data-Link – Example: Mücke Jamming UAV System (viewgraphs 43 to 46)

The Mücke UAV System is used for jamming of enemy communication systems at VHF and above using jamming equipment developed by Dasa in Ulm. As a consequence a microwave Data-Link cannot be used for EMI reasons.

The tasks of the Data-Link in the Mücke System are confined to data transfer for Jammer Control, Status and Position Request and Reporting and updating of the Mission Plan.

This results in an overall data rate of ~ 1 kb/s, which can well be accommodated by an HF Link.

The requirements to the link allow to base it on military-of-the-shelf equipment (MOTS). In this case components of the HRU 7000 system, developed by Dasa in Ulm for long-range reconnaissance forces of the army, were used:

- The HRU 7000 digital transceiver, which covers the HF spectrum with an output power of 30 watt. This transceiver also includes a link processor to control frequency hopping and co-ordination of the semi-duplex communication with its counter part. A digital HF modem is also included.
- The ATU 7000 Antenna Tuning Unit allows to match whip antennas, random wires and dipoles over the whole HF spectrum.

As the Mücke UAV is a relatively small A/V with a wingspan of ca. 3.5 m and a length of ca. 2.5 m integration of an efficient HF antenna is a challenge. Full-size dipole antennas covering 2 MHz to 12 MHz would have a length between 80 m or ca. 12 m respectively.

A shortened horizontal dipole antenna with capacitive loading was integrated into the wing-edge of the UAV and is matched by a modified ATU 7000 to the HRU 7000. Ranges of more than 400 km can be achieved with this configuration

As can be seen from this example even small UAVs can be equipped with an HF-Link for long-range non-line-of-sight communication using COTS hardware if low data rate can be tolerated.

Microwave UAV Data-Link – Example: BREVEL Reconnaissance UAV System (viewgraphs 47 to 59)

A high-sophisticated data-link has been developed in a co-operation of **DaimlerChrysler Aerospace** and **MATRA Systemes & Information** for the **BREVEL RECONNAISSANCE UAV System**. This system has been jointly developed by Germany and France between 1992 and 1998.
The BREVEL System is a highly mobile UAV System for deployment in close proximity to the battlefield. Consequently the exposure to ECM is very high and the data link equipment has to withstand extreme environmental conditions.

BREVEL Operational Tasks (viewgraph 48)

The BREVEL System is used for reconnaissance missions over the battlefield area using an IR camera. In addition to that targets detected in the footprint of the UAV sensor shall be located with a precision, that allows engagement of that target by weapons like MLRS or SMArt 155 to their maximum engagement range.

Design Drivers for the BREVEL Data-Link (viewgraph 49)

Concerning the data-link this mission requires

- an extremely high resistance to jamming
- low detectability
- the ability to correct errors
- flexibility in the anti-jamming characteristics from mission to mission
- precise localization of the UAV
- survivability to battlefield conditions like NEMP

BREVEL Data-Link Design Choices (viewgraph 50)

For the above requirements a digital Data Link is the logic choice.

Due to the digital nature of the Radio Frequency signals a digital link allows powerful information- and signal processing, that is not possible to the same extent with the analog data-links still deployed in most UAV systems today.

A digital link is the basis, on which the most performant spread spectrum techniques and error correction techniques can be applied. Together with an uplink and a downlink, which exist at the same time on different frequencies, a so-called full-duplex solution the anti-jamming performance is further improved and propagation delay between UAV and ground can be measured very precisely.

The link becomes even less vulnerable through the use of highly directional antennas, which also improve the link budget and are the basis for tracking of the UAV and measurement of the UAVs direction.

Localization Function (viewgraph 51)

The localization function is a special design feature of the BREVEL Data-Link, which allows to determine A/V localization with sufficient accuracy for engagement of ground targets in the footprint of the imaging sensor. This makes the system independent of the GPS P/Y code.
The localization function requires knowledge of AV direction and AV slant range relative to the Data Link Vehicle (DLV) and the height of the AV. Together with accurate knowledge of the DLV location this information allows precise location of the Air Vehicle.

In the ground data terminal the monopulse principle, which is widely used in radar systems, is used for direction measurement.
For monopulse measurement special circuitry is used to generate two antenna diagrams, one of which has a maximum in the boresight of the antenna, while the other diagram has a sharp notch in this direction.
This feature allows to precisely determine the direction to the Air Vehicle within the beam of the antenna of the GDT. Together with precision mechanics, which have to even compensate for bending of the mast in the wind, the direction in a reference grid is determined.
The slant range to the Air Vehicle can be calculated from the propagation delay, which can be very accurately measured from the code synchronisation in transmitter and receiver.
The height above sea level is measured in the ADT and transmitted via the data link.
In addition to localization, the monopulse principle is used to track the Air Vehicle from the GDT so that a very narrow-beam antenna can be used, which reduces the vulnerability to jamming and relaxes the need for transmitter power.

BREVEL Data-Link Technology (viewgraphs 52, 53)

The Data Link is made up of an Airborne Data Terminal (ADT), which is located in the BREVEL Air Vehicle, and a Ground Data Terminal (GDT) fitted on the mast of the Data Link Vehicle. These equipments will be described in more detail later.
The following design features have been applied to both equipments.

- high modularity to satisfy the maintainability and also to facilitate the integration between antenna, microwave- and base-band technology.
- identical technology in the two equipments to harmonize the dual functions and also to simplify the spare parts.
- use of identical subunits in ADT and GDT wherever possible.
- ASIC technology for base-band processing
- use of solid state microwave power amplifiers
- highly compact synthesizers
- use of modular microchip thin films microwave circuits
- use of chip carriers components on collaminated Printed Circuit Boards for signal processing circuits
- Status monitoring.

Key Design Features

The Ku frequency-band has been chosen for operation of the BREVEL Data-Link, as it allows directional antennas of reasonable size to provide an excellent compromise between range and anti-jamming performance.

Unless extreme jamming and weather conditions occur a range in excess of 150 km is achieved with this link.

This range is determined by the television channel, which is currently dimensioned for a data-rate of 10 Mb/s. A substantially higher range is possible for Telecommand and Telemetry channels.

The BREVEL Data-Link is designed to provide

- a high level of protection associated with very low level of detectability
- high accuracy of UAV localization under severe jamming conditions
- compatibility with severe environmental conditions including Nuclear Electro-magnetic Pulse (NEMP)

The very high degree of performance is achieved by means of specific techniques:

- combined Frequency Hopping (FHSS) and Direct Sequence Spread Spectrum (DSSS) modulation working full duplex for: Telecommand, Telemetry and Tele-vision.
- Non-coherent detection providing higher reliability, efficiency and robustness against sporadic signals compared to straight forward designs based on carrier phase recovery.
- detection and correction codes (FEC) optimized on both random errors and message reconstruction.
- High-speed synchronization process for shorter acquisition and reacquisition time due to specific Surface Acoustic Wave (SAW) matched filters.
- possibility of self adaptive level of transmitted power to minimize detectability and to take the most advantage of the transmitter power available on board.

- highly directional antennas with high gain, low side lobes and accurate motorization.
- design of the most complex functions at base-band level providing maximum flexibility for possible adjustments and future growth potential.
- calibration free ranging technique
- high ranging accuracy thanks to short time DSSS chip.
- unbiased monopulse processing for high azimuth localization accuracy under jamming conditions
- high dynamic range of the receiver associated with intelligent automatic gain control (AGC) strategy to cope with the high level of jamming signals.
- sophisticated and very accurate built in test (BIT) designed to diagnose Line Replaceable Units (LRU) without any specific operational maintenance test equipment.
- high scale integration for devices (ASICs) offering the best compromise between:
  - volume/weight
  - power consumption/temperature
  - processing power/complexity
  - availability/reliability.

BREVEL Air Vehicle (viewgraph 54)

The Airborne Data Terminal is fitted in the BREVEL Air Vehicle (A/V).
The A/V is relatively small with a length in the of ca. 2,3 meters, about 3,4 meters wingspan and a take-off weight of approx. 150 kg.

Air Data Terminal (ADT) (viewgraph 55)

The Air Data Terminal (ADT) of the BREVEL Data Link has been specifically designed taking into account the UAV constraints :

- **Aerodynamic:** the board antenna is installed in the tail fin of the UAV with minimum impact on the flight characteristics of the UAV.
- **Weight:** The Air Data Terminal has the lowest weight impact of all the electronic devices embedded in the UAV.
- **Thermal Conditions:** the electronics are divided in three units:
  - the Electronic Unit installed in the electronic bay of the UAV.
  - the Front-End (including power amplifier) installed in the rear of the UAV
  - the Board-Antenna on the tail-fin of the UAV.

  This permits to split the thermal dissipation and to dispatch it in the UAV and also to offer possibilities of growth potential. The Front-End and the Board-Antenna are the only frequency-sensitive components, and can be redesigned to suit the required transmitted power and/or frequency.
- **Accessibility:**
  - Antenna mounting occurs from the tail-fin side
  - Electronic Unit is installed on a trail in the electronic-compartment
  - Front-End has a small size and is easily accessible in the fuselage.

The Board-Antenna is pointed to the ground-station from a direction calculation based on A/V position, attitude and north-orientation. A special function compensates for eventual errors of the A/Vs north-reference.

The ADT features a MIL-BUS Interface to the A/Vs flight control system and RS 422 interfaces to the compression unit of the UAV camera to provide continuous on-line video.

The total ADT weight is in the order to 10 kg.

BREVEL Data Link Vehicle (viewgraph 56)

The BREVEL Data Link Vehicle (DLV) is a small 1-axel trailer, with a retractable fold-over mast, which carries the GDT and the power unit for GDT operation. The DLV can be located more than 1 km away from the manned Ground Control Station in order to protect personnel from anti-radiation weapons.

Ground Data Terminal (GDT) (viewgraph 57)

The Ground Data Terminal (GDT) of the BREVEL Data Link has been specifically designed taking into account the ground constraints :

- The GDT combines features of a precision tracking radar (without the radar transmitter) with the primary Data-

Link function. This way precise localization of the UAV is achieved.

- **Stabilization of the GDT:** due to the high level of accuracy for localization of UAV position through the Data-Link, a very performant stabilization of the ground antenna is mandatory.
- **Mechanical performances:** A sophisticated mechanical design has been chosen in order to handle the high performance antenna.
- **Protection:** the GDT is designed to conform with environmental constraints: NEMP, lightning, contamination with-out any damage.
- Communication with a remote control center through a fibre-optic link.

All GDT electronics and mechanics are located inside a spherical radome. Opening of the radome allows access to all components.

The GDT design allows tactical and logistical driving in most severe terrain without any damage to the high-precision mechanics and electronics. The overall weight of the GDT is about 160 kg.

Status of the BREVEL Data-Link (viewgraph 58)

DaimlerChrysler Aerospace and **MATRA Systemes & Information** have developed the BREVEL Data-Link between 1992 and 1998. A total of 17 Air Data Terminals and 5 Ground Data Terminals have been built for Industry Trials and Troop Trials.

The last deliveries have been made in April 1998 at the beginning of troop trials. Prior to that the BREVEL system has performed two flights in Finland in arctic winter climate. During these flights the data-link has performed without any failures. Long Range performance could be demonstrated during these flights.

More than 95 flights with data-link, amounting to over 90 flight-hours have occurred.

Germany has decided procurement of the BREVEL System and **STN ATLAS Elektronik** has received a contract for Serialization and Production of the System.

The serialization- and production-activities for the data-link by **DaimlerChrysler Aerospace** and **MATRA Systemes & Information** are planned to start in the third quarter of 1999.

Potential for Evolution (viewgraph 59)

Due to its modular design the BREVEL data link described above allows to adapt one or a few subunits to changing requirements without affecting the remaining part of the design. For example the following modifications could be envisaged.

- Antenna (different beamwidth, frequency range)
- Antenna stabilization (different accuracy)
- Front End (different transmitter-power, frequency band)
- Electronic Unit (different interface to A/V or ground station, increase of data-rate).

Also functions may be added (e.g. data compression) or deleted/simplified (e.g. A/V localization precision).
Such changes can be made without significant impact on the architecture of the design and with limited changes in software.
To summarize the design of the data link allows adaptation to a broad spectrum of requirements and has the potential to tailor its complexity to provide cost-effective solutions for requirements of extremely-high to medium sophistication.

SUMMARY (viewgraph 60)

UAV Data-Links have to satisfy requirements for

- maximum feasible range
- high mobility
- low mass and size
- high reliability and jamming resistance
- high data rates for such UAVs, which are equipped with imaging sensor.

If all of the above requirements apply no standard of-the-shelf solution exists and the data-link has to be designed to come to a cost-effective trade-off.

This may be done starting from an existing design. The BREVEL data link is an example, of a starting point, which satisfies all of the above requirements in a line-of-sight microwave data-link.

COTS solutions are available, which can satisfy a subset of the requirements

- The Mücke Link satisfies all of the requirements in an HF link with the exception of high data rates.
- The SATCOM link used in GLOBAL HAWK satisfies the requirements with the exception of low mass and size and with some restrictions on jamming resistance.

These examples show that all variants

- HF
- Microwave
- SATCOM

have their place in the UAV world.

DaimlerChrysler Aerospace is the Competence Center in Germany for UAV Data Links and is one of the leading developers and suppliers for Microwave and HF Data-Links.

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UAV Data-Links: Tasks, Types, Techniques and Examples

UAV Data-Links:

Task, Types, Techniques

and Examples

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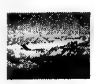
DaimlerChrysler AG

1998 . Revenues DM 257.8 bn, € 131.8 bn

Workforce 442,000

Automotive			Non-Automotive			
Passenger Cars	Passenger & Commerc. Cars	Commercial Vehicles	Aerospace	Chrysler Financial Services	Services	Other Businesses
						
▪ Mercedes-Benz ▪ Smart	▪ Chrysler ▪ Plymouth ▪ Jeep ▪ Dodge	▪ Mercedes-Benz ▪ Freightliner ▪ Sterling ▪ Setra	▪ Commercial Aircraft ▪ Helicopters* ▪ Military Aircraft ▪ Defense and Civil Systems ▪ Aero Engines ▪ Space Infrastr. ▪ Satellites *40% stake	▪ Leasing ▪ Commercial Financing ▪ Conventional Financing	▪ Financial Services ▪ Telecommunication & Media Services ▪ IT Services	▪ Rail Systems ▪ Automotive Electronics ▪ MTU/ Diesel Engines
Revenues DM 63.8 bn € 32.6 bn Workforce 95,200	Revenues DM 110.1 bn € 56.3 bn Workforce 123,200	Revenues DM 45.4 bn € 23.2 bn Workforce 89,700	Revenues DM 17.2 bn € 8.8 bn Workforce 45,900	Revenues DM 5.7 bn € 2.9 bn Workforce 3,500	Revenues DM 18 8 bn € 9.6 bn Workforce 20,200	Revenues DM 6.6 bn € 3.4 bn Workforce 32,600

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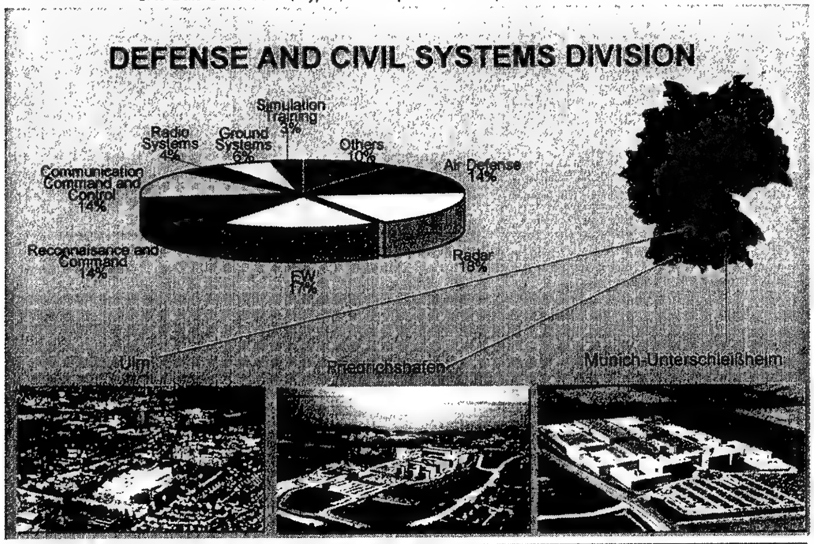

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DASA ULM - Data-Links for UAV and Missile-Systems

Current Data-Link Projects:

- **KZO BREVEL Data-Link** (production-ready)
- **Naval Drone SEAMOS DL** (Definition Phase)
- **CL289 Data-Link Upgrade** (Feasibility Study)
- **Data-Link for HALE UAV** (Feasibility Study)
- **Data-Link for ESM-UAV** (Feasibility Study)
- **Data-Link for Naval Stand-off weapon KEPD-150 SLM** (Feasibility Study)
- **ROLAND Surface to Air Missile Data-Link** (After Sales Support)
- **MEADS Surface to Air Missile Data-Link** (Feasibility Study)
- **MJ2000 Sonar-Data Transmission** (Definition Phase)
- **HF-Data-Link for Mücke Jamming Drone** (Development)
- **HF-Data-Link for TAIFUN Attack Drone** (Definition Phase)

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UAV DATA - LINK

TASKS AND REQUIREMENTS

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TYPICAL UAV MISSIONS

- Reconnaissance, Surveillance, Damage Assessment
- Suppression of Enemy Air Defense (SEAD)
- Target Search and Attack
- Target Localisation for Artillery Engagement
- COMINT and ELINT
- Jamming

MOST OF THESE MISSIONS REQUIRE A DATA LINK

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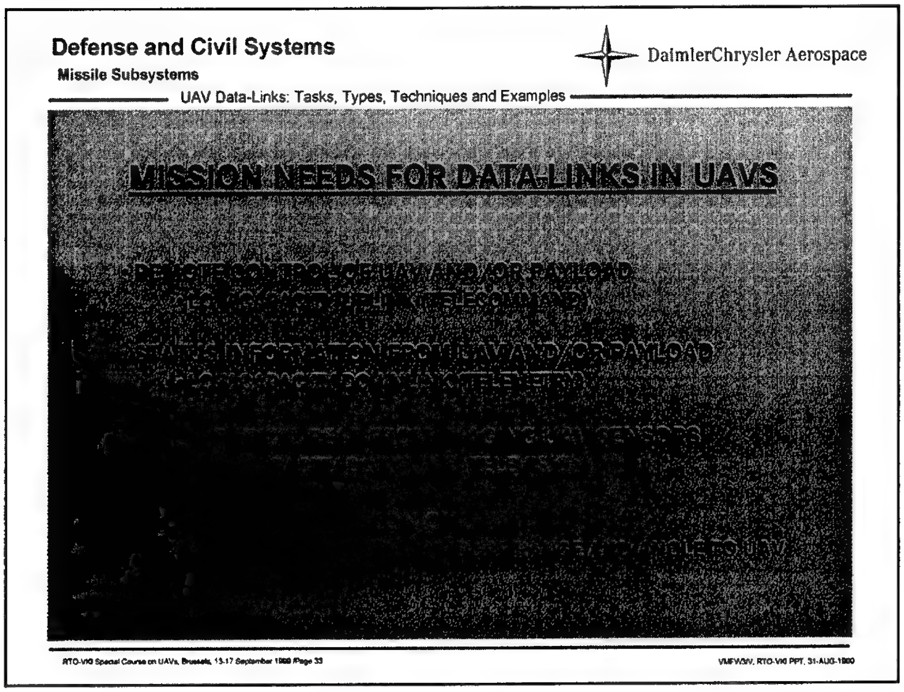
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MISSION NEEDS FOR DATA-LINKS IN UAVS
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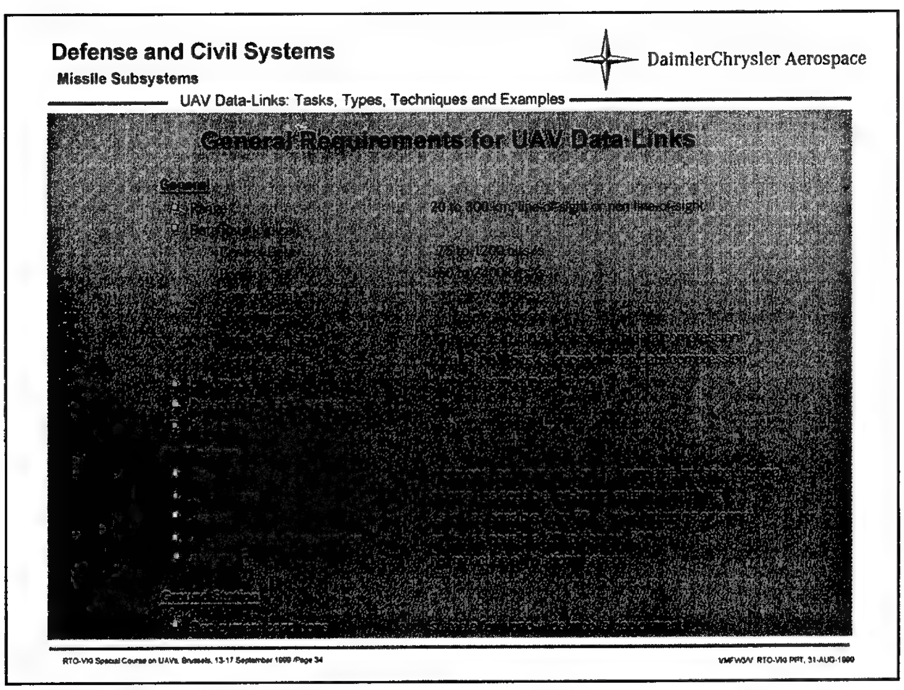
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General Requirements for UAV Data Links
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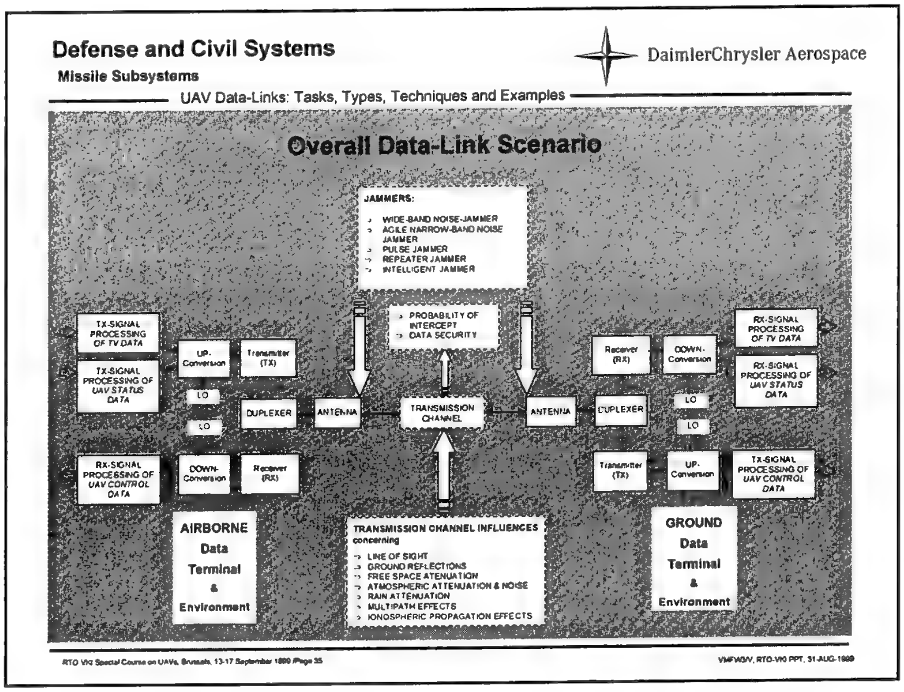
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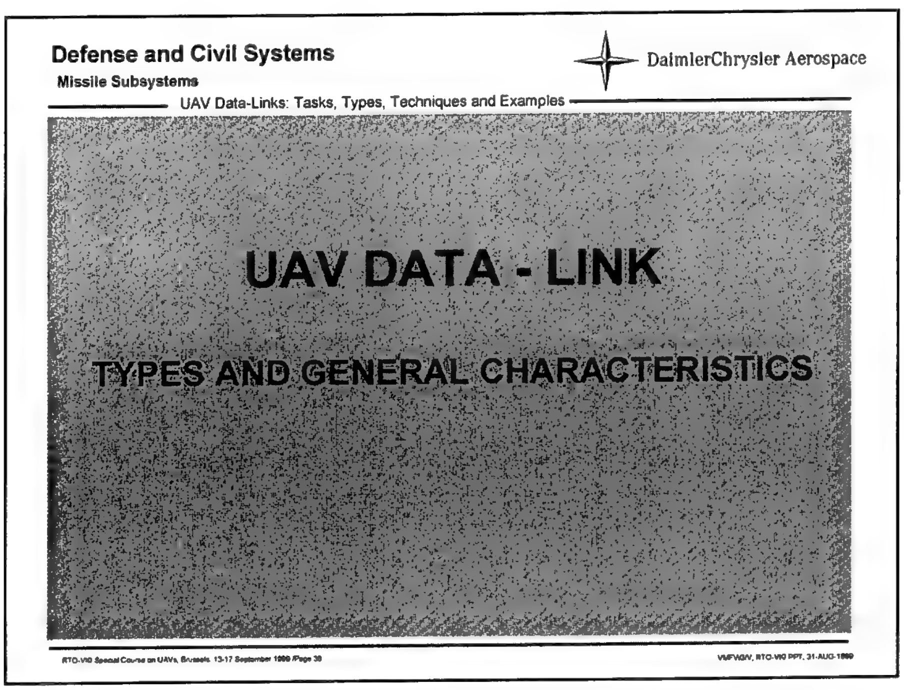
Overall Data-Link Scenario
JAMMERS:
WIDE-BAND NOISE-JAMMER
AGILE NARROW-BAND NOISE JAMMER
PULSE JAMMER
REPEATER JAMMER
INTELLIGENT JAMMER
PROBABILITY OF INTERCEPT
DATA SECURITY
TX-SIGNAL PROCESSING OF TV DATA
TX-SIGNAL PROCESSING OF UAV STATUS DATA
RX-SIGNAL PROCESSING OF UAV CONTROL DATA
UP-Conversion
Transmitter (TX)
LO
LO
DUPLEXER
DOWN-Conversion
Receiver (RX)
ANTENNA
TRANSMISSION CHANNEL
ANTENNA
DUPLEXER
Receiver (RX)
DOWN-Conversion
RX-SIGNAL PROCESSING OF TV DATA
RX-SIGNAL PROCESSING OF UAV STATUS DATA
LO
LO
Transmitter (TX)
UP-Conversion
TX-SIGNAL PROCESSING OF UAV CONTROL DATA
AIRBORNE Data Terminal & Environment
TRANSMISSION CHANNEL INFLUENCES concerning
LINE OF SIGHT
GROUND REFLECTIONS
FREE SPACE ATENUATION
ATMOSPHERIC ATTENUATION & NOISE
RAIN ATTENUATION
MULTIPATH EFFECTS
IONOSPHERIC PROPAGATION EFFECTS
GROUND Data Terminal & Environment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UAV DATA - LINK
TYPES AND GENERAL CHARACTERISTICS

ANALOG versus DIGITAL

- Analog Links transmit the information by means of amplitude-, frequency- or phase-modulation
  (e.g. AM/FM Broadcast, Television)

  They are still in use in many UAV systems.
  These links are generally not jam-resistant and robust.

- Digital Links convert the analog signal into a digital data-stream, which is transmitted by means of Phase-Shift- or Frequency-Shift-Modulation.

  This allows to manipulate the signal in such a way that a great degree of jam-resistance and robustness can be achieved

  They are the Future

Data-Rate and Bandwidth

Robust Standard Modulation Techniques (e.g. BPSK) usable for UAV Data-Links require:

Data-Rate r (Bit/s) ≈ net Band-Width B (Hz)

For technical reasons feasible band-width is related to transmitted frequency:

max. usable Bandwidth B(Hz) ≈ 3% of Transmit Frequency (Hz)

Jam-Resistance can be achieved by multiplying the net band-width:

Approximation for jam-resistant UAV-Data-Links:

Bandwidth B (Hz) ≈ 2...1000 * Data-Rate r (Bit/s)

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Frequency Bands for UAV Data-Links

100GHz
10GHz
1GHz
100MHz
10MHz
1MHz
100kHz

Micro-Wave: (SHF)
- Generally Line-of-Sight Communication
- high gain with small antennas
- narrow beam antennas possible
- high data-rates possible
- limited transmitter efficiency

VHF / UHF:
- Propagltion by LOS or Reflection and Diffraction
- relatively large antennas
- Data-Rates limited to <2MBit/s

Short-Wave: (HF)
- no Line of Sight required
- Ground- or Sky-Wave propagation
- dependent on solar activity, time of day, location
- only low data-rates (<10kBit/s) feasible

LW, MW

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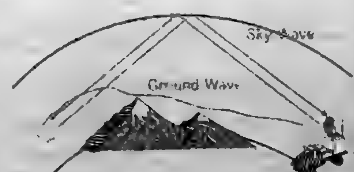
UAV Data-Links at HF-Frequencies (Shortwave)

Propagation not dependent on Line-of-Sight:

1. Ground-Wave (Deflection, Reflection, Diffraction)
2. Sky-Wave (Ionospheric Reflection)



Typical Characteristics:

1. Link Quality very dependent on Time, Location and Frequency
2. Low Data-Rates (<10kBit/s) due to low frequency and propagation effects
3. Frequencies above ca. 12 MHz cannot be used reliably in a UAV System
4. Range up to ca. 500 km with > 90 % availability, independent at UAV altitude

HF UAV Data-Links allow long-range communication without line of sight.
Due to limited data-rates at HF they are limited to Telecommand or Telemetry Data and Transmission of still images.

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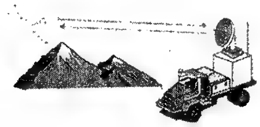
UAV Data-Links at Microwave



Characteristics of Microwave Data-Links:

- Line of Sight Propagation (LOS)
- Range up to a few 100 km (dependent on UAV altitude and terrain)
- High Transmit Frequency allows extremely high Bandwidth (several 100 MHz)
- High Bandwidth allows High Data-Rate and optimum Jamming Resistance
- High Transmit Frequency facilitates Narrow-Beam Antennas (Jammer Suppression, LPI)
- Long Range independent of UAV altitude and terrain requires an Airborne Relay

For small tactical reconnaissance UAVs a LOS-Microwave-Data links provide an optimum solution as they can combine high data-rates with optimum jamming resistance at reasonable size and weight.

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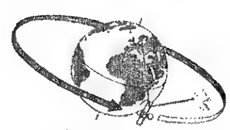
UAV Satellite Links



General Characteristics:

- World-Wide Coverage possible. Only depends on Number and Orbit of the Satellites used
- Extremely high Data-Rates (>100MBit/s) possible due to high transmit frequency and line-of-sight condition

Problems / Restrictions:

- UAV Antenna-System for wide-band transmission of sensor data is heavy and big
- Uplink UAV -> Satellite can be jammed with relative ease
- Military Communication Satellites are currently not in the inventory of european countries.

Wide-Band satellite-based Data-Links are primarily used for HALE-UAVs (HALE: High Altitude, Long Endurance) which require world-wide coverage and can tolerate high volume and mass. Wideband-Satellite-based links are currently not yet an alternative for smaller (tactical) UAVs !

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UAV DATA - LINK

DESIGN ASPECTS & TECHNIQUES

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UAV Data-Links: Tasks, Types, Techniques and Examples

MAIN CONSIDERATIONS FOR DATA-LINK DESIGN

- AIR VEHICLE CONSTRAINTS
  - antenna type and size, transmitter power
  - Size, Weight and Power Consumption
- LINK BUDGET AND QUALITY
  - gain and losses balance for Signal to Noise Ratio
- LINK PROTECTION AND QUALITY
  - side-lobe suppression
  - robustness of modulation
  - anti-Jamming techniques
- FLEXIBILITY, COMPLEXITY AND COST

➔ TRADE-OFFS ARE REQUIRED

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UAV Data-Links: Tasks, Types, Techniques and Examples

Definition of the System Quality Figure of a Communications Link

System Quality =	**Radiated Power** from Tx in the direction toward Rx	–	**Minimal Detectable** Signal Power (Rx Sensitivity) of Rx in the direction toward Tx	=	**Maximum Allowable Path Loss**

Radiated Power:

- Nominal Transmitter Power
- Modulation Loss (Crest Factor)
- Antenna Matching / Matching loss
- Antenna Gain (Directional Gain x Efficiency) in the direction towards Rx (Elevation, Azimuth)

Minimal Detectable Signal:

- Receiver Noise Figure
- Antenna Matching / Matching Loss
- Antenna Gain (Directional Gain x Efficiency) in the direction towards Tx (Elevation, Azimuth)
- Bandwidth (Data Rate)
- Minimal Signal / Noise (S/N) Ratio (dependent on Modulation Type)

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Link-Budget: Data-Link Signal Power

Power density at distance d:

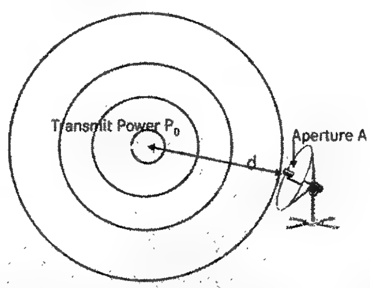
$p = P_0 / (4\pi d^2)$

Signal Power at Antenna:

$P = p A = P_0 A / (4\pi d^2)$

Antenna Gain G in dB:

$G = 10 \log (4\pi A / \lambda^2)$



Received Signal Power at RX input in dBm (dB above 1 mW) is thus calculated as

$$S/dBm = P_0/dBm + G - 10 \log (4\pi d/\lambda)^2$$

Signal Power at RX (dBm)

Transmit Power (dBm)

Antenna Gains (Airborne + Ground)

Free Space Attenuation as a Function of Range and Wavelength

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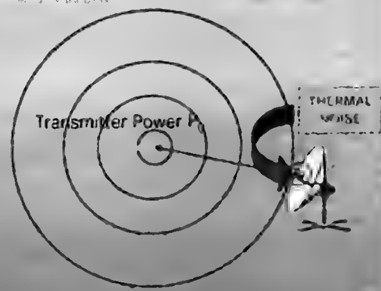
Link-Budget: Noise Power

Thermal Noise is the result of molecular movement in the components of the receiver. Thermal Noise Power is given as

$N = k\,T_0\,B$

- k = Boltzmann Constant 1,38 10^{-23}Ws/K
- T = Temperature (generally 300K)
- B = Receiver Bandwidth



Considering the Relation Bandwidth B ~ Data-Rate r and the constants k and T_0 Noise Power at the receiver input can be derived from the formula

$$N/dBm = -174dBm + 10\log(r)$$

Noise Power at Rx (dBm)

Constant: $10\log(kT_0)$

Data-Rate dependent

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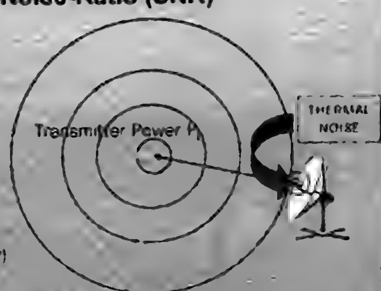
Link-Budget: Signal-to-Noise-Ratio (SNR)

Signal-to-Noise-Ratio allows an initial rough judgement of data-link performance. It includes the major influences. Further influences are introduced by

- Cable and Radome losses, etc.
- Losses from multi-path effects
- Synchronization Losses
- Weather attenuation (e.g. 0.1dB/km at 10GHz)
- Jamming



The Signal-to-Noise-Ratio at the Receiver can be calculated as:
(atmospheric noise and jamming not taken into account)

$$SNR = 10\log\frac{P_0 \cdot g \cdot \lambda^2}{k \cdot T_0 \cdot r \cdot (4 \cdot \pi \cdot d)^2} = P_0/dBm + G - 10\log(4\pi d/\lambda)^2 - 10\log(kT_0 r) \overset{!}{\geq} 10dB$$

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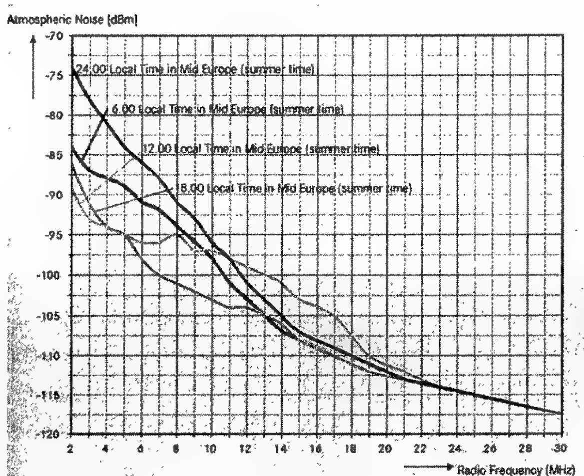

Atmospheric Noise as a function of Radio Frequency at different local times (Winter, Sun Spot Number = 75, Mid Europe)

Frequencies above ca. 12 MHz are generally not reliable for use in a UAV System

Minimum Sensitivity is largely determined by atmospheric noise

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Typical Path-Losses and Antenna Parameters for UAV Data Links

Frequency (GHz)	λ (cm)	Free-Space + Atmospheric Attenuation for 180 km	Free-Space + Atmospheric + Rain Attenation for 180 km	Total Gain ADT+GDT Antenna (dBi)	Az-Beam (GDT)	AZ-Beam (ADT)
0,4	75	130 dB	130 dB	≈ 20	≈ 25°	360°
2	15	145 dB	145 dB	≈ 25	≈10°	360°
5	6	153 dB	153 dB	≈ 40	≈ 4°	≈ 35°
10	3	159 dB	162 dB	≈ 55	≈ 2°	≈ 12°
15	2	164 dB	171 dB	≈ 65	≈ 1°	≈7°

Rain is assumed with a density of 4mm/h over 25% of the path

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Link-Budget: Examples

Examples for a UAV-Data-Link in Ku-Band (15 GHz) for TV-transmission (r=5 Mbit/s):

Influence	Example1 (Omni-directional Antenna)	Example 2 (Directional Antenna)
SNR required	10dB	10dB
Noise Power at r=5MBit/s	-107dBm	-107dBm
Free Space Attenuation for 100km	156dB loss	156dB loss
Rain Attenuation (0,15dB/km)	15dB loss	15dB loss
Receiver Noise Figure	3dB loss	3dB loss
Antenna Gains (Airborne + Ground)	0dB gain	64dB gain
System Losses	4dB loss	4dB loss
Fading Margin	10dB loss	10dB loss
Required TX Power in UAV	91 dBm = 1200 kW Not feasible!	27 dBm = 0,5W

This Link-Budget for a typical UAV Data-Link makes it obvious that directional high-gain Antennas are mandatory.

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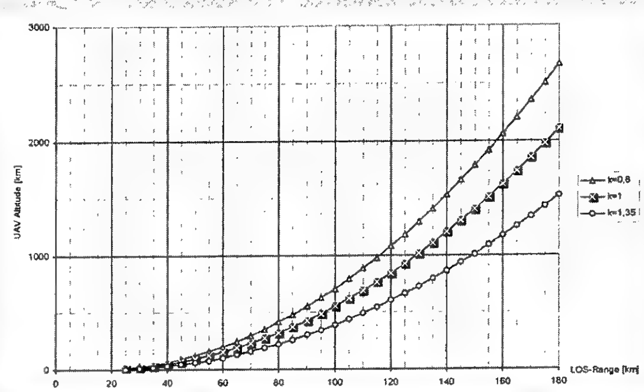
Line of Sight Range of Microwave Link vs. UAV Altitude



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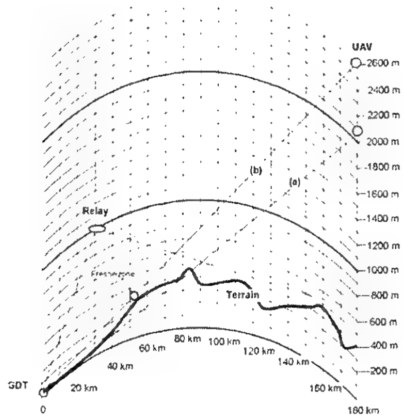
Terrain Masking Effects on Line of Sight Range



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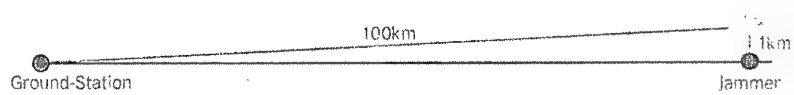
Jamming - Resistance



For equal transmitter power of ground-station and Jammer the UAV receiver sees:

Jamming Power $J = 100^2 \bullet$ Power of Data-Link Signal --> Factor of 10000 equals 40dB !

Suppression of Jammers can be achieved by:

- Narrow-Beam Antennas
- Direct-Sequence Spread-Spectrum
- Frequency-Hopping Spread-Spectrum
- Channel Coding

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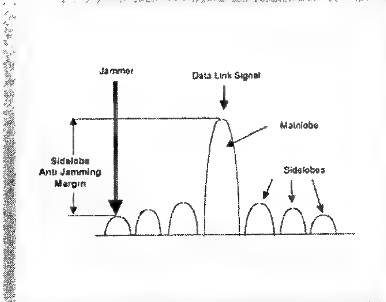
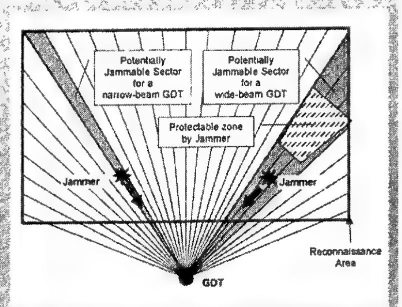
Anti-Jamming Effect of Highly Directional Antennas





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Suppression of Jammers by Narrow-Beam Antennas

- Jammers are largely limited to the main-lobe
- Jammer Suppression ≥ Side-Lobe suppression (e.g. > 20dB)
- Width of main-lobe is inversely proportional to antenna size
- Width of main-lobe is inversely proportional to frequency
- Jammable area decreases with beam-width

Directional Antennas should be used in the UAV and on ground!
For a given antenna-size jammer suppression increases with frequency!

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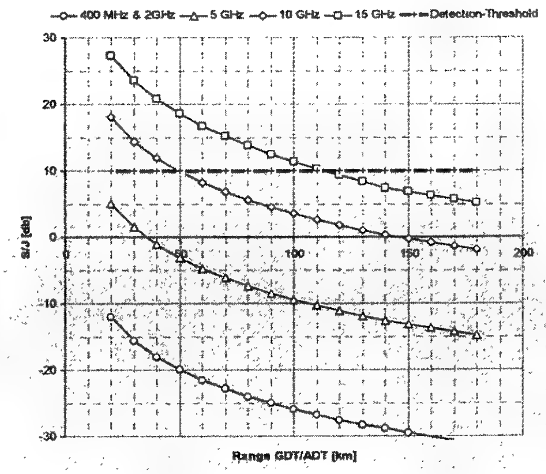
Down Link Range under Severe Jamming Conditions



Power: 1 W

Antenna Gain (ADT)
Size - limited by constraints of tactical UAVs

typically between 1 dBi at 0,4 GHz and 23 dBi at 15 GHz

Antenna Gain and Sidelobes (GDT)
Size - limited by cross-county capable Data-Link Vehicle

typically between -15 dB side-lobes and 18 dBi gain at 0,4 GHz and -28 dB side-lobes and 40 dBi gain at 15 GHz

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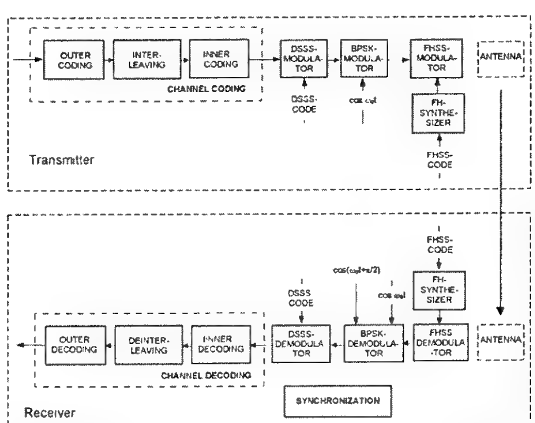
Typical Digital Data-Link Processing



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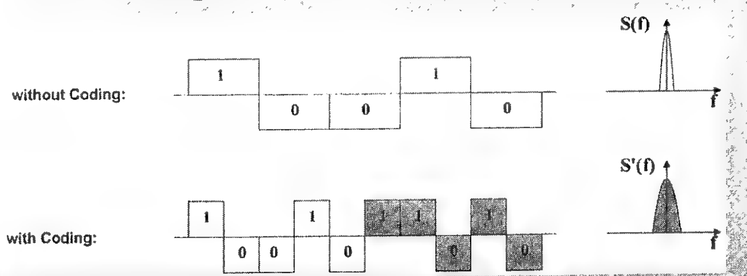
Channel Coding for Improvement of Bit Error Rate (BER)



TX Side:	Introduce Redundancy (additional Bits according to Coding Algorithm)
RX Side:	Use Redundancy to Detect and Correct Bit-Errors
Result:	In spite of increased bandwidth for the same TX-Power (➡ lower S/N) the Bit-Error-Rate can be reduced
Examples:	Block-Codes: BCH-Codes, Reed-Solomon-Codes, Hamming-Codes, CRC Convolutional Codes: various constraint lengths and generator-polynomes

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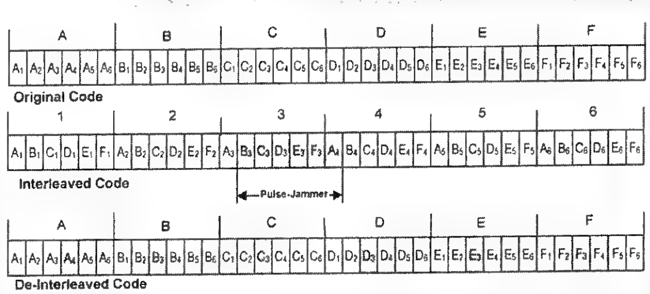
Anti-Jamming Effect of Interleaving



Effect of Pulse Jammer can be transformed to limited effects, which can be corrected by Error-Correction Coding

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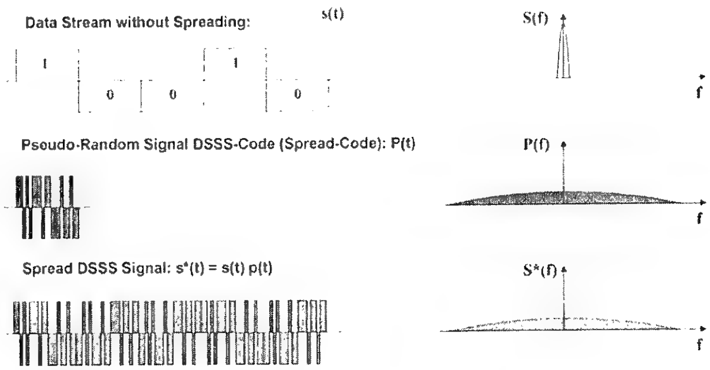
Generation of Direct-Sequence-Spread-Spectrum (DSSS)



The transmitted DSSS Signal is generated by multiplication of the digital data-stream and a spread. This results in a wide-band signal with low spectral density, which facilitates Jamming-Resistance and Low-Probability of Intercept.

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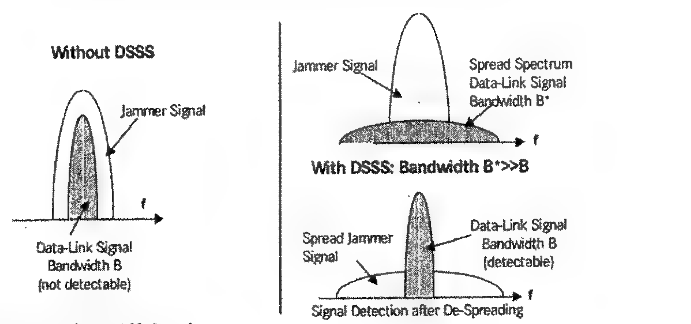
ANTI - JAMMING EFFECT of Direct Sequence Spread-Spectrum



Spot-Jammers and most Noise-Jammers can be suppressed by DSSS

Processing Gain=Spreading Factor = B*/B

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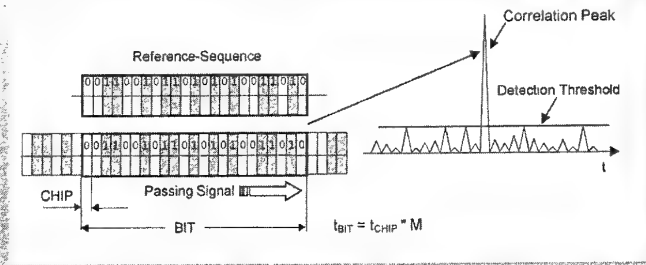
DE-SPREADING OF DSSS SIGNAL BY CORRELATOR



$t_{BIT} = t_{CHIP} * M$

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Frequency Hopping Spread Spectrum

Pseudo-Random Change of Center-Frequency Between N Channels

- **forces jammer to spread energy over n channels**
  >> jammer efficiency reduced by 1/n
- **effect of jammer, which stays in only 1 channel can mostly be compensated by channel-coding**
- **Fading- and Multipath-Effects are minimized by FHSS**

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Design Summary for Wide-Band Data-Links

Design Feature	Reason / Potentaial
Use of Ku-Band (15 GHz)	• NATO-Recommendation for future UAV-Data-Links • facilitates high bandwidth • narrow antenna-beam Jam-Resistance
Directional Antenna (Ground and Airborne)	• Best Link Budget (Range) • low probability of intercept (LPI), high jamming resistance • allows UAV position measurement and tracking • Minimization of multi-path effects (stability)
Direct-Sequence Spread-Spectrum	• low probability of intercept (LPI), high jamming resistance • precision measurement of UAV range
Frequency-Hopping Spread-Spectrum	• further improvement of LPI and jamming resistance • Minimization of multi-path effects by inherent Frequency-Diversity
Optimized Channel Coding	• Improvement of Bit Error Rate at given S/N • Correction of Clustered Errors from Pulse Jammers

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UAV DATA - LINK

EXAMPLES

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UAV Satellite Links - Example: Global HAWK

Characteristics of HALE-UAVs:

- Range ca. 25000km
- max. altitude ca. 20000m
- Mission-Time up to ca. 40h
- Sensors: SAR, EO, IR, MTI, ...

Characteristics of the SatCom-Link:

- Uplink UAV -> Satellite in Ku-Band (15GHz)
- Data-Rate 1,5MBit/s (one channel) up to 47MBit/s (multiple channels)
- Commanded Parabolic Dish (∅1,25m)

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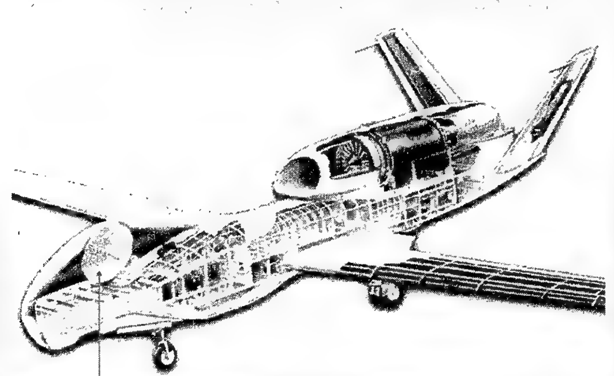
UAV Satellite Links - Example: Global HAWK



Ku-Band SatCom-Antenna with 1,25m diameter
Stabilization and Pointing of the Antenna requires ~ 1m³ Volume

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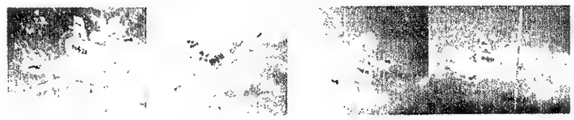
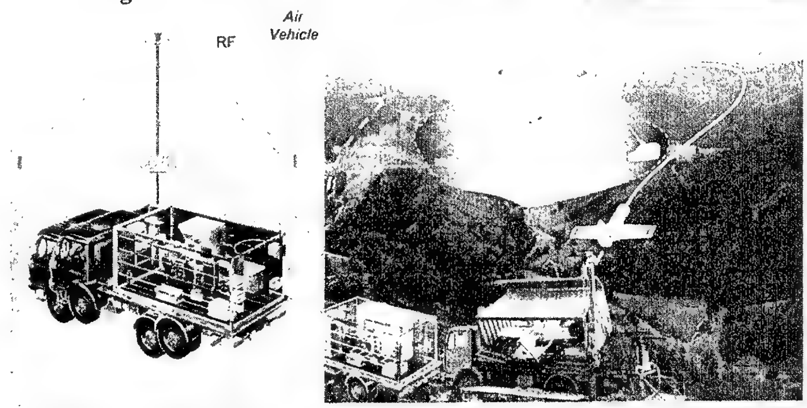
**Example:
HF Data Link for
MÜCKE
Jamming Drone**





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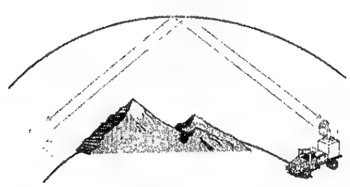
HF UAV Data-Links
Example: Jamming Drone MÜCKE



HF Data-Link Characteristics

- Bidirectional Link (TC-Uplink and TM-Downlink)
- Multiple Transmission, FEC-Coding, Frequency-Diversity and cyclic Frequency-Hopping to maximize Link-Availability
- Data-Rate ≈ 1kBit/s, Range ≈ 400km, Availability 70% bis 90%

Data-Link Tasks

- Uplink TC: Control of Jammer, Request for Status and Position, Change of Mission Planning
- Downlink TM: Status and Position Reporting

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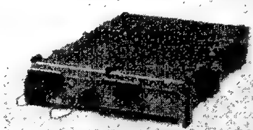
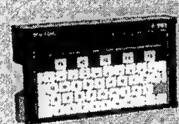
HF Radio Mobile HRM 7000 (portable)



HF-Transceiver HRU 7000
- HF Output Power 30 Watt
- Link Control Processor
- HF Modem

Antenna Tuning Unit ATU 7000
- Whip Antennas 3,3m to 7m
- Long Wire Antennas 7m to 16m
- Dipole Antenna DPA 7000



Terminal TCU 7000
- Display 2 lines, 40 characters
- Soft-Key Man Machine Interface
- 2x Memories for Report and Command Messages
- Embedded Crypto Unit

Power Supply
- Accumulator Power Unit APU 7000 (NiCad, 5Ah)
- Battery Power Unit BPU 7000 (Lithium, 20Ah)

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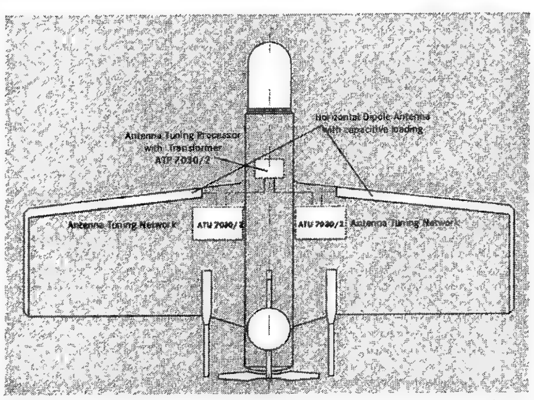
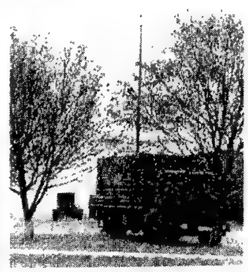
MÜCKE JAMMING UAV



Horizontal HF Dipole Antennas integrated in Drone (electrical length extended via capacitive loading)



MÜCKE
GROUND CONTROL STATION
WITH
GROUND DATA-LINK TERMINAL

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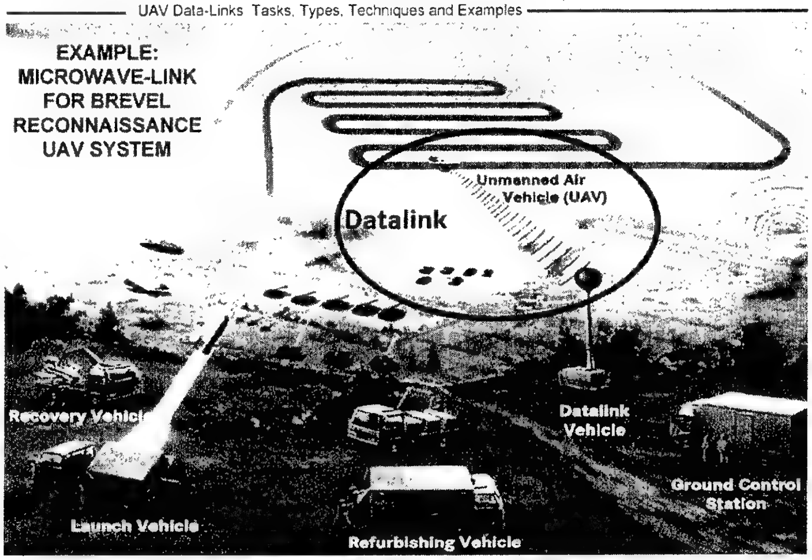

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BREVEL Operational Tasks:

- **Reconnaissance over the Battlefield**
- **Target Detection**
- **Target Localization for Engagement by MLRS, SMArt 155, etc. to maximum weapon-range**
- **Mission Time : several Hours**

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Design Drivers for BREVEL Data-Link:

Provide Television and Status Downlink & Control Uplink with

- **Extremely High Jamming Resistance**
- **Low Detection Probability of Data-Link Signals**
- **Error Correction Capabilities**
- **Very high Accuracy for Measuring the Drone's Location**
- **High Electromagnetic Compatibility Requirements (NEMP)**
- **Flexibility in Changing of Codes for Each Mission**

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BREVEL DATA-LINK DESIGN CHOICES

- **A Digital Data-Link allows**
  - forward error correction
  - most performant spread spectrum techniques
- **A Full Duplex Data-Link**
  - allows very accurate synchronisation of transmitter and receiver
  - improves spread spectrum performance
  - allows precise measurement of propagation delay
- **Highly directive Antennas**
  - allow tracking and angle-measurement
  - improve link budget and jam-resistance

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UAV Data-Links Tasks, Types, Techniques and Examples

Localization Function

Achieved through

- precise angle-measurement in GDT by monopulse principle (Sum- and delta-channel with sophisticated signal processing)
- calculation of ADT range from propagation delay (accurate measurement by spread spectrum synchronisation algorithm)

Gives exact coordinates for engagement of the targets in the footprint of the UAV's imaging sensor

Allows extremely narrow antenna beam in GDT for

- improvement of link budget
- jamming protection
- ADT tracking by GDT

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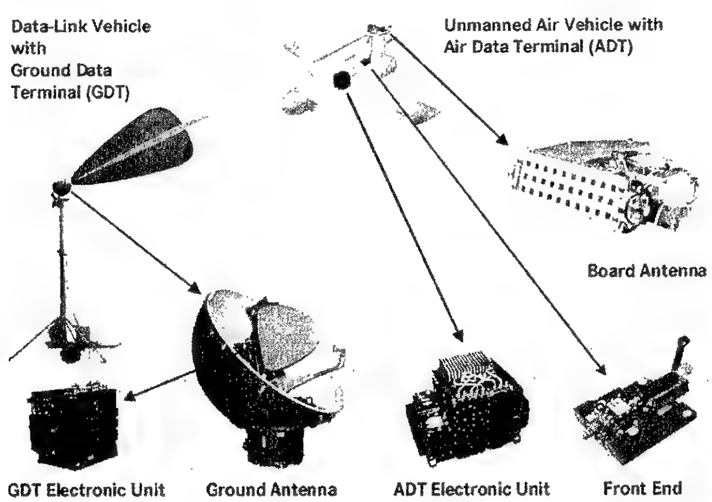

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Key Design Features:

- Frequency Band: Ku-Band
- Range: > 150 km
- Data Rates Uplink: 10 kb/s Command Channel
  Downlink: 10 kb/s Status Channel
  10 Mb/s Payload Data
- Full Duplex
- Combined Frequency Hopping- and Direct Sequence Spread Spectrum
- 2-Level Channel Coding optimized for anti-jamming
- A/V Localisation and Tracking (Range and Azimuth)
- Highly directive Antennas with automatic tracking
- Solid State Transmitter with adaptive Power Management capability
- Field Servicable (LRU Concept)
- Highly Modular
- Very low Bit- and Frame Error Rates

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Defense and Civil Systems
Missile Subsystems

DaimlerChrysler Aerospace

UAV Data-Links: Tasks, Types, Techniques and Examples

BREVEL Air-Vehicle

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Defense and Civil Systems
Missile Subsystems

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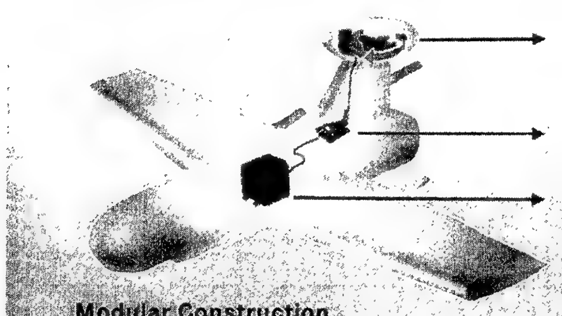
UAV Data-Links Tasks, Types, Techniques and Examples

Air Data Terminal (ADT)



Modular Construction
allows adaption to
- Thermal and Space Constraints
- Future Changes in Power and Frequency
gives optimum maintainability

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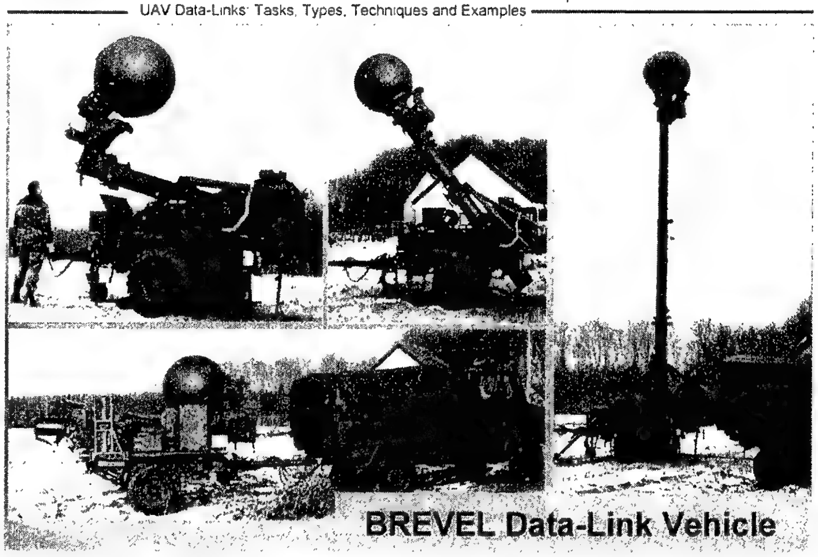

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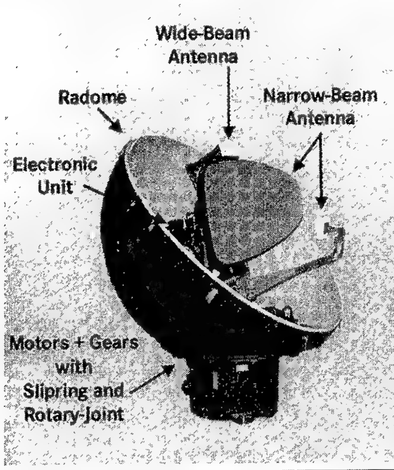
Ground Data Terminal (GDT)



combines
RADAR TECHNOLOGIES
for precision tracking of air-vehicle

and
SIGNAL PROCESSING TECHNOLOGIES
for error-free jam-resistant communication

with
FIBER-OPTIC LINK TO GROUND-CONTROL STATION
for EMC and NEMP Protection

Defense and Civil Systems
Missile Subsystems
DaimlerChrysler Aerospace
UAV Data-Links: Tasks, Types, Techniques and Examples

STATUS OF BREVEL DATA-LINK

- 17 Airborne Data Terminals (of 22) and
- 5 Ground Data Terminals (of 7)

built for Industry-Trials and Troop Trials until April 1998

- Troop Trials under way since April 1998
- More than 95 data-link flights (> 90 hours)
- 2 flights in artic climate
- Serialization/Production Start planned for 3rd quarter of 1999

GROWTH POTENTIAL

Modular Design and flexible Architecture allow

- **Range Increase by Simple Exchange of Power Stage**
- **Advanced Adaptive Power Management Algorithms**
- **Change of Interfaces**
- **Addition of Functions (e.g. data compression)**
- **Data Rates up to 50 Mb/s without change of concept**
- **Change of Frequency Band possible with partial exchange of subunits only**

Summary

- UAV Data-Links are subject to complex requirements
  - high mobility
  - high data rates
  - high jamming resistance
  - low mass and size
- Military UAV Data-Links are usually adapted or designed to offer an optimum trade-off between these requirements for the specific application
- Major Variants
  - HF Link
  - Satellite Link
  - Microwave Link
- DaimlerChrysler Aerospace, Ulm, is the German Competence-Centre and leading System Supplier for UAV Data-Links

The Development and Operational Challenges of UAV and UCAV Airbreathing Propulsion

(September 1999)

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22195 Elmer Road, Unit 4
Patuxent River, MD 20670 USA

INTRODUCTION: There are a large number of Unmanned Aerial Vehicles (UAVs) throughout the world performing a variety of functions. The variety of conditions under which they operate, e.g., speed, altitude, endurance, VTOL, payload etc. impact or limit the type and size of propulsion system needed.

This paper will define the various UAV categories and will characterize the types of engines and propulsors available for them. The variability of design features and their effect on characteristics will be shown. The effect of propulsion system trades on total system capability will be discussed.

CATEGORIZATION OF UAV's: Various organizations have used different categories to distinguish various types of UAV's. These categories have varied between organizations and at different times even within one organization. In addition, these categories often related to the usage of the UAV (e.g. Strategic or Tactical) or organizations using them (Corps or Platoon) rather than the items that affect propulsion needs.

For the purpose of this paper we have chosen to categorize UAV's into five discrete categories representing five diverse types of propulsion requirements. We have named these categories **Local, Regional, Endurance, Quick Look,** and **UCAV** (Uninhabited Combat Aerial Vehicle).

The **Local** category of UAV is most challenged by the fact that the equipment must be small, easily supported and potentially expendable. It is intended to be operated by a small group of soldiers with perhaps only one or two vehicles in a very mobile, volatile environment. There would be no time for extensive setup or maintenance. The equipment must be capable of being moved quickly and be economical enough that it could be willingly abandoned, if necessary. Figure 1 illustrates this category pictorially.

The propulsion challenges for the Local category of UAV are:

a) Compactness / Portability
b) Efficient low power class engine
c) Light weight
d) Minimum support equipment
e) Low cost

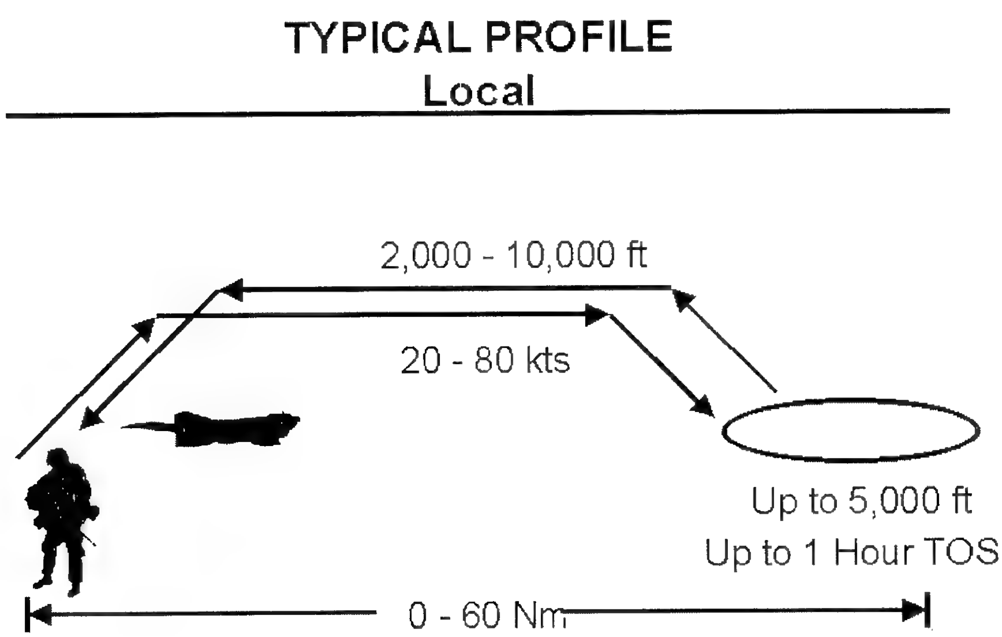


FIGURE 1

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.

TYPICAL PROFILE
(Regional - Land / Ship Based)

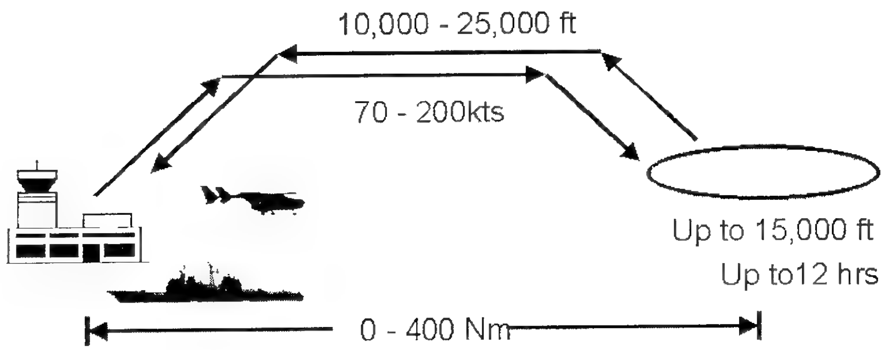


FIGURE 2

The **Regional** category is broken into two subcategories based upon the operating bases. The operating range, endurance, altitude and payloads are similar but the operational bases necessitate some differences in propulsion. Figure 2 illustrates this category pictorially.

The **Regional/Land based** subcategory is assumed to have a semi-fixed operating base with support and facilities. As such, it could have greater capabilities than the local category. Missions could be longer and, even though restricted to a region for which that organization is responsible, could be rather long range thus necessitating good propulsion reliability. A moderate length runway can be assumed to be available. Even though the facility is semi-fixed it is still assumed to be within a hostile military environment so that simplified maintenance and operation with commonly available battlefield fuels is important.

The propulsion challenges for the Regional / Land based category of UAV are:

a) High fuel efficiency at cruise and loiter
b) Operation with battlefield fuels
c) Simplified maintenance / modularity
d) Reliability
e) Low cost

The base for the **Regional / Ship based** subcategory is assumed to be aviation capable ships. This includes ships which have only helicopter capability. This will then necessitate a VTOL capability. This VTOL capability will demand a high power to weight ratio for the propulsion system since the vehicle will be lifted off the deck by virtue of brute force from the propulsion system with no wing to provide lift multiplication. Missions are relatively long duration and long range. The possibility of retrieval in an ocean environment is minimal. Therefore high propulsion reliability is necessary. The operations must fit within the normal shipboard routine and capabilities. Simple maintenance and operations with fuels normally carried on board the ship are mandatory.

The propulsion challenges for the Regional / ship based category of UAV are:

a) VTOL capability
b) Ship operational compatibility
c) Operation with shipboard fuels
d) Simplified maintenance / modularity
e) Excellent power to weight
f) Reliability
g) Low cost

TYPICAL PROFILE
Endurance

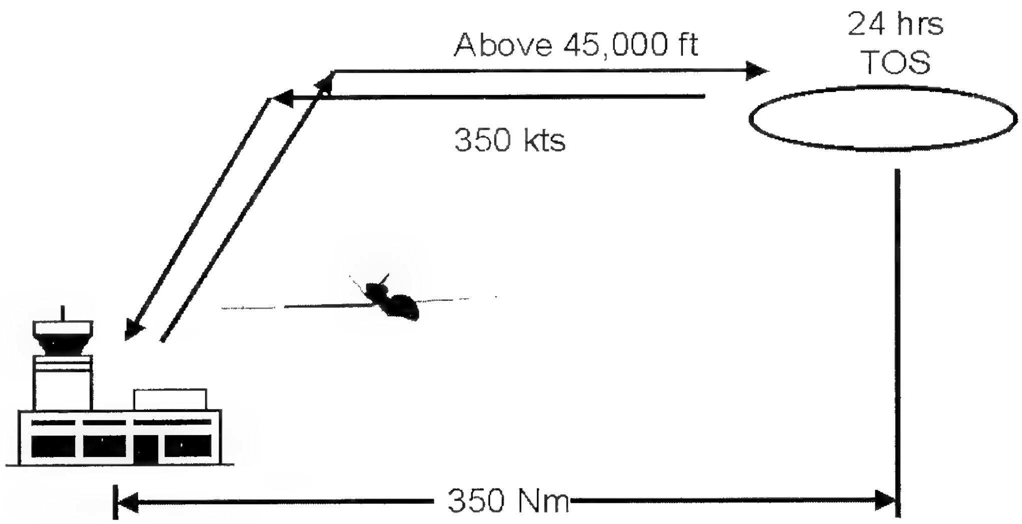


FIGURE 3

While the very title of the **Endurance** category tells us that high altitude and fuel efficiencies are required, reliability and good climb performance are also necessary even though not as immediately obvious. Reliability is important because the system could very well be very far out and at high altitude to achieve a mission. Large quantities of time, effort and money have been expended on getting the vehicle on station. A propulsion system failure in mid mission results in a loss of all this expended effort as well as the aborting of a mission that perhaps was relevant only at that specific time. The loss of the vehicle is also virtually assured.

Good climb performance is necessary not only because the mission is performed at high altitude but because the vehicle will be heavy with fuel at the beginning of the climb due to its planned long mission. Figure 3 illustrates this category pictorially.

The propulsion challenges for the Endurance category of UAV are:

a) Excellent mission reliability
b) Excellent fuel efficiency
c) High altitude capability
d) Good climb performance
e) Low cost

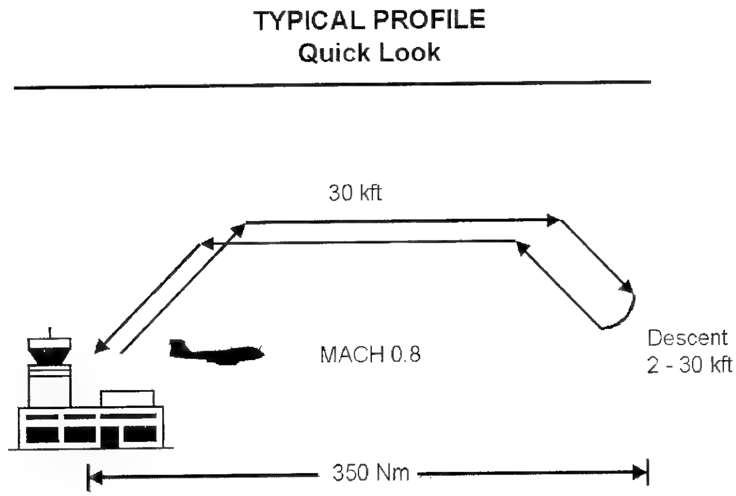


FIGURE 4

The **Quick Look** category is essentially an unmanned version of a fighter/reconnaissance type aircraft. While high thrust to weight and good efficiency at high mach number are characteristic of any high performance fighter aircraft these must be achieved at lower cost and with simpler maintenance than a fighter. The prime reason for this is that if it cannot be achieved at lower cost with simpler maintenance, why not just use a manned fighter type aircraft for reconnaissance as has been done since WWI ? It must be remembered, however, that the same question was asked about cruise missiles. The question was answered with low cost expendable engine technology which is very relevant to this category. Figure 4 illustrates this category pictorially.

The propulsion challenges for the Quick Look category of UAV are:

a) High thrust to weight
b) Good efficiency at high mach number
c) Simplified maintenance / modularity
d) Reliability
e) Low cost

As generally envisioned today, the primary **UCAV** challenge will be the same as for any modern high performance military aircraft, i.e. high thrust to weight. The unique challenge in the UCAV, however, is the fact that this system is stored for most of its life rather than constantly in use for training missions.

Another challenge which could exist is the capability to withstand higher maneuvering loads if the designers choose to take advantage of the fact that there would be no pilot physiological limitations. Figure 5 illustrates this category pictorially.

The propulsion challenges for the UCAV are:

a) High thrust to weight
b) Storage capability (wooden round)
c) Maneuvering load capability
d) Low cost

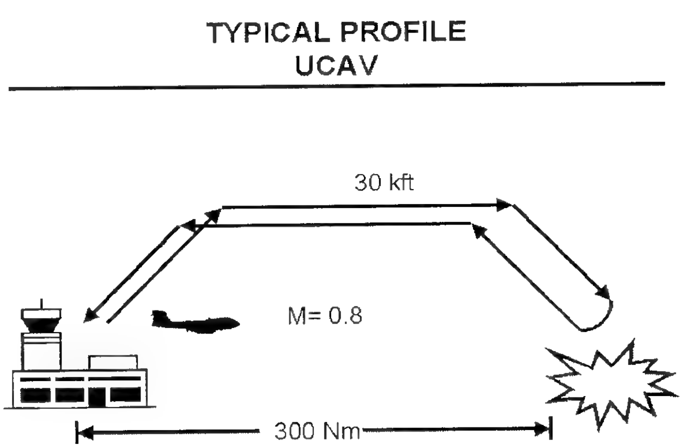


FIGURE 5

SYSTEMS ENGINEERING: This paper will illustrate the many options in propulsion with their greatly varying characteristics. These variations enhance the ability of the systems engineering team to make productive tradeoff studies involving propulsion. The application of systems engineering assures a balanced influence of all required design specialties, resolves interface problems and performs trade studies. Using a systems engineering approach for propulsion selection is desirable because it lessens the probability of unexpected propulsion system modification or replacement after deployment.

The need for a systems engineering approach (i.e. clean sheet vs. off the shelf selection) involves continuous and selective trade studies in which the propulsion system will be stressed so that the *right* engine and propulsor is selected for the application. Systems engineering involves trade-off studies at each level in the development process. The process shown in figure 6 describes the type of propulsion solutions that will be developed at each level in the process.

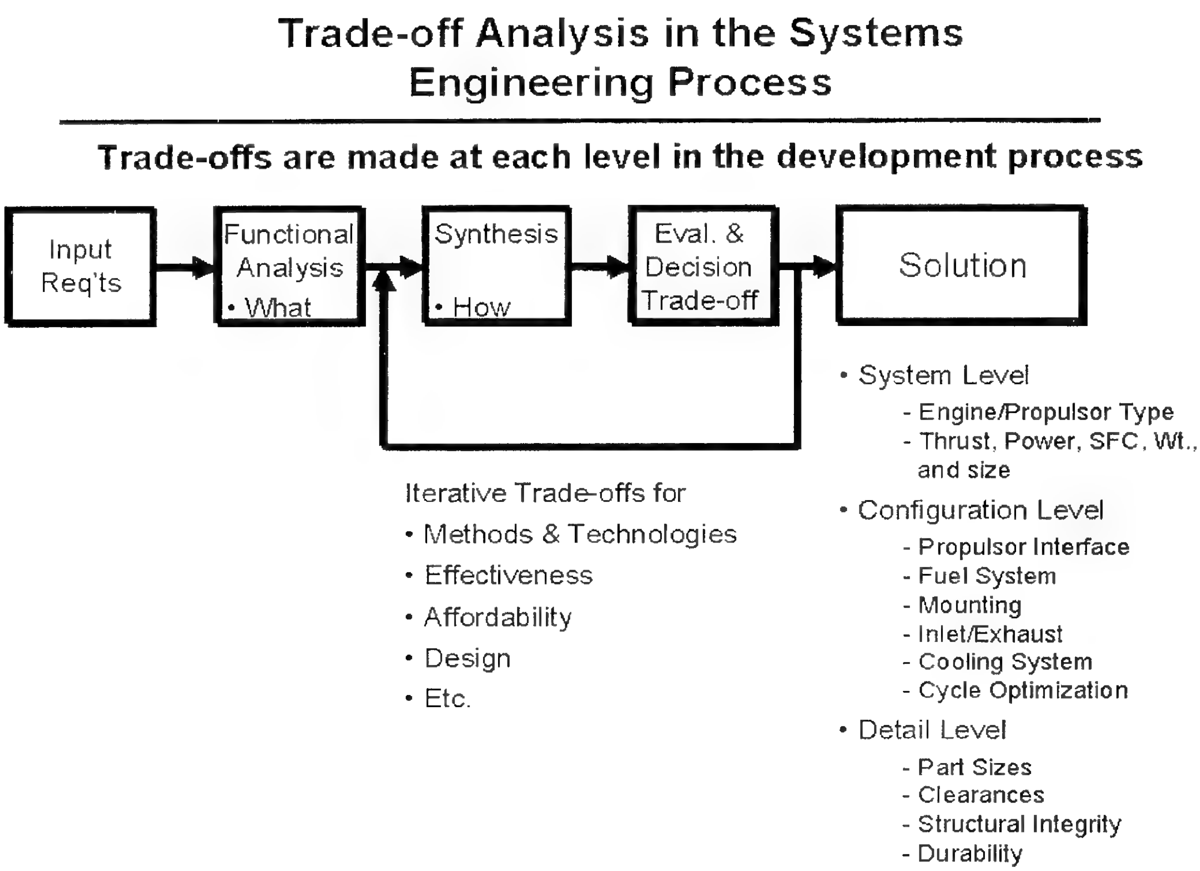
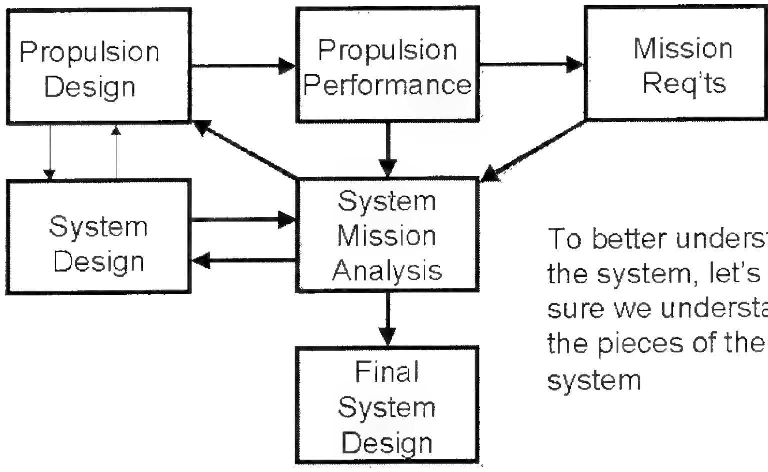


FIGURE 6

PROPULSION SELECTION
A SYSTEMS PROBLEM

A Typical process we use to identify the optimum propulsion system is shown below:



To better understand the system, let's be sure we understand the pieces of the system

FIGURE 7

Good System Engineering *requires* early propulsion trade studies. A typical process used in these studies for sizing and selecting the optimum propulsion configuration is shown in figure 7. The selection process is initiated by the overall system mission requirements which include mission profiles, operating envelope and environmental requirements. These parameters provide initial guidance for the class of propulsion system desired and may also aid in setting initial bounds on the range of design variables to be investigated. Analysis for a combination of independent propulsion system design parameters (such as disc loading, engine rotational speed etc.) initiates the process in the ***Propulsion Design*** block shown. A systematic variation of these variables leads to the definition of propulsion performance parameters such as thrust, fuel efficiency, weight and dimensions for each set of independent variables. These are integrated with the airframe configuration and design variables to develop aircraft figures of merit such as Take Off Gross Weight, Thrust-to-Weight ratio and wing loading and performance parameters such as landing distance, acceleration time, maneuver loads, and specific excess power. The propulsion system is selected based on the desired aircraft performance and design variables.

A comparison of the Global Hawk and Pioneer systems illustrates the advantages of applying early trade studies in the acquisition process. In the Global Hawk program, propulsion studies and characterizing tests were performed early in the program. The result was a low cost variant of a commercial engine.

In contrast, the Pioneer program was procured as a non-developmental item. No early propulsion trade studies and tests were conducted. The engine used in the application was procured "off-the-shelf". The result was that changes were required to the propulsion system early in the program to overcome carburetion and fuel system problems. In addition, when early attempts were made to replace the engine with one more suitable, the efforts and costs required to change an in service system were found to be overwhelming. Durability changes to the original engine are still being made after 13 years of operational use.

Propulsion System Operational Limits

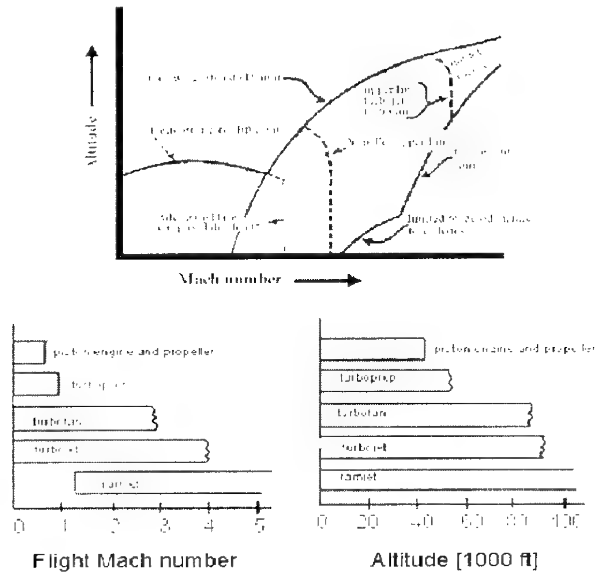


FIGURE 8

PROPULSION SYSTEM OPERATIONAL LIMITS: Figure 8 illustrates the operational ranges of various types of propulsion systems within envelopes of operational aircraft limits. The leftmost envelope represents a helicopter with a horizontal rotor propulsion system. The rotor propulsion system of a helicopter is limited in altitude by the control limits of the rotor pitch and decrease in the available engine power at altitude. The interaction of these effects yields the rounded top to the figure. Helicopter Mach number is limited by the compressibility effects on the advancing rotor blade.

The curved figure on the right represents fixed wing aircraft with propeller, fan and jet nozzle propulsion systems. Gross separation in fixed wing propulsion types (i.e. propeller vs. turbofan and turbojet) by speed are a result of compressibility effects on the propeller. Selection of the engine and associated propulsor (i.e. rotor, propeller, fan, nozzle) in overlapping operational conditions are based on trade studies that involve parameters such as disk loading, fuel consumption, various efficiencies etc. The propulsion system selection process will be discussed in more detail later in this paper.

PROPULSOR TYPES: A propulsion system consists of a **Propulsor**, the device that directly provides the moving force (thrust) to the vehicle and an **Engine** or prime mover. We will present all of these individually and then their various combinations.

Propulsors: There are four major types of propulsor devices. These devices and their definitions are:

Rotor- A device consisting of rotating airfoils which achieves lift and/or thrust depending upon its orientation. Propulsive thrust (and/or lift) is achieved by an increase in momentum of the air passing through it.

Propeller- A device consisting of airfoils rotating about an axis generally parallel with the direction of flight. Propulsive thrust is achieved by an increase of momentum of the air passing through it.

Fan- A device similar to a propeller but encased in a peripheral shroud thus permitting a higher momentum and pressure increase in a smaller diameter.

Nozzle- A device which converts the energy in a gas to velocity. Thrust is achieved by the momentum increase in the gas stream. (jet propulsion)

Engines: There are three major types of engines or prime movers used in UAV's. these engines and their definitions and subtypes are:

IC Engine- Intermittent Combustion engine. An engine that burns and exhausts its charge in repeating or intermittent cycles. The three major types of IC engines are:

SI Engine- Spark Ignition Engine. The common automotive type gasoline engine wherein the charge is throttled to vary power and a homogeneous charge is ignited by a spark or glow plug.

CI Engine- Compression Ignition Engine. The common Diesel engine wherein an unthrottled charge is introduced into the combustion chamber and compressed to a high pressure and temperature. Fuel is injected into the charge and autoignites. Power is controlled by varying the amount of fuel injected.

AI Engine- Assisted Ignition Engine. A low compression ratio engine which operates on the heavy fuels common to a Diesel engine. Since the compression ratio is not high enough for autoignition, a spark or glow plug or both is used to assist ignition. The lower compression ratio permits a lighter engine structure than a true Diesel.

2.) Gas Turbine Engine- An engine operating to the Brayton cycle. During this cycle air is compressed, fuel is added and burned at constant pressure and a turbine is finally used to provide energy for driving the compressor. The remaining energy in the hot gas is then used to provide shaft power or propulsive thrust. The three major types of aviation gas turbines are:

Turboshaft/Turboprop- A gas turbine engine which generates power by expansion of a vitiated fuel/air mixture through a turbine. The term turboprop is used to refer to a turbine integrated with a propeller. Turboshaft is used to refer to an engine which drives any other propulsor.

Recuperative Turboshaft- A turboshaft engine wherein heat is extracted from the exhaust gases and used to add heat to the process gases thus saving fuel. The Recuperative turboshaft engine is a special case of the turbine engine and, as such, is a slight modification to the Brayton cycle. This modification will be discussed later.

Turbojet/Turbofan- A turbine engine which achieves thrust by accelerating gases through a nozzle. (Jet Propulsion) In a turbofan a portion of the accelerated gas does not pass through the combustor. The Turbojet/ Turbofan engines are actually package propulsion systems composed of a nozzle or fan propulsor (or both) combined with a turbine prime mover.

3.) Electric- An electric propulsion installation generally consists of an electric motor as a prime mover, wiring, a power controller device, and an energy storage and / or generation device. Power storage is generally accomplished with a secondary battery. Energy generation is accomplished by means of solar cells or fuel cells. A hybrid propulsion system might consist of a fossil fueled engine which generates power for an electric propulsion system.

PROPULSOR CHARACTERISTICS: The primary characterizing parameter of an aircraft propulsor is its **Disk Loading** which is defined as the propulsive thrust divided by the cross sectional area of the propulsor disk through which the propelling fluid flows.

Figure 9 shows that as we progress from static to ever higher velocities the optimum disc loading increases. Ultimately, however each type of propulsor fails when the tip velocity of the airfoil approaches sonic speed. This is why transonic speeds had to wait for the development of the jet engine.

Notice that there is always an overlap. The reason for the overlap of each of the propulsors is that within each category there can be a variation in disc loading. That overlap and the fact that any system's missions will be flown at varying velocities illustrates the need for trades. The only place where the decision is clear is the static situation (hover). Here a large diameter rotor would be appropriate. But the minute any forward velocity is desired the situation again demands trades. The trades involving disc loading will be discussed in detail later.

Propulsors
Disk Loadings vs. Cruise Speed

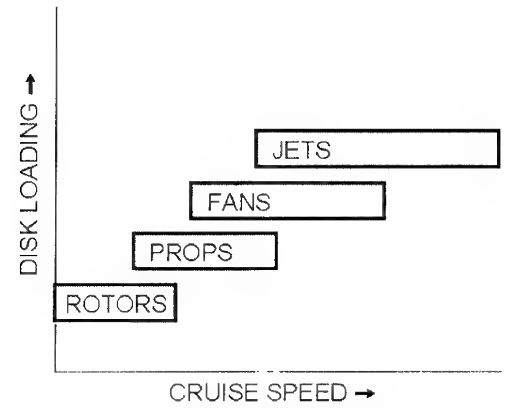
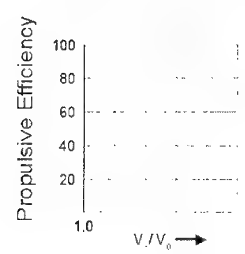


FIGURE 9

Propulsive Efficiency



where: $V_e / V_o = 1+(T/\rho V_o^2 A)$

Therefore at any given flight velocity and thrust

- Efficiency is greater with lower velocity increase
- Efficiency is greater with larger disk area
- Efficiency is greater with lower disk loading

FIGURE 10

Propulsive efficiency at any flight speed is dependent upon the ratio of the propulsor exit velocity to its inlet velocity as shown on figure 10.

Even though lower disk loadings produce higher propulsive efficiencies they have some very definite limitations at higher flight velocities. Figure 10 does not consider compressibility effects which are significant at higher Mach numbers. In addition, for a fan, the peripheral shroud on large fans becomes a significant source of drag.

Low disk loading devices will have a lower thrust to weight ratio which can be a significant detriment on high performance aircraft. Also low disk loading devices require low rotational speeds which may be incompatible with the prime mover unless a gearbox is added. This, of course, will increase the weight and complexity of the system. The conclusion, then, is that disk loading requires mission optimization trades to achieve the best system solution.

Engine Weights

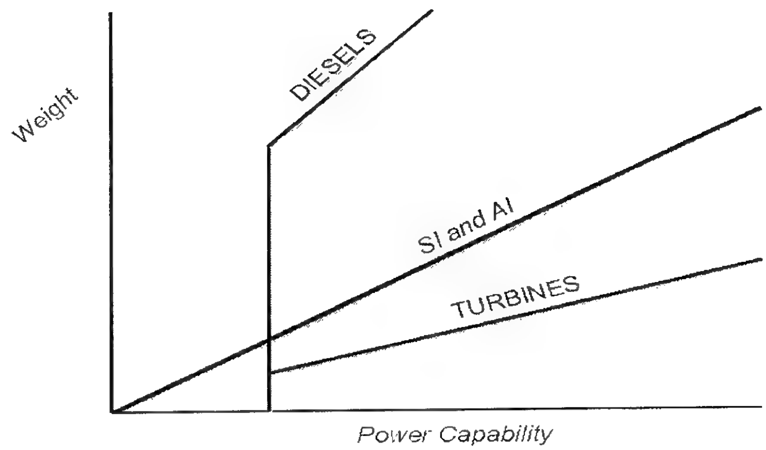


FIGURE 11

ENGINE CHARACTERISTICS: The primary engine characteristics subject to trades are **Weight, Power, Efficiency and Reliability**. The three different types of engines discussed and their subtypes all have very different characteristics.

Weight- The engine types vary markedly in their weight characteristics. This is dramatically illustrated in figure 11.

The lower horsepower limit for diesels and turbines shown on this slide is about 100 horsepower. This leaves the under 100 horsepower regime to Spark Ignition engines.

Power- The one power regime in which the SI gasoline engine has a clear advantage is in the very small sizes. These engines, because of their small combustion chamber sizes and high rotational speeds do not have a great susceptibility to detonation. For this reason they can be operated at high compression ratios and high Brake Mean Effective Pressure (BMEP). In addition, because of their favorable high area to volume ratio, cooling is relatively easy, again allowing operation at high BMEP with lightweight cooling schemes. Since there is no need for a direct fuel injection system, these system weights, which can only be made so small despite the engine size, are eliminated.

The two stroke air cooled type especially provides simplicity and light weight in the smaller sizes. These engines suffer in that they are not particularly durable, require frequent overhauls, emit an environmentally dirty exhaust, and use a real nuisance fuel which consists of gasoline mixed with special two stroke oils. Any Pioneer operator will verify all these attributes but, in spite of them, the Pioneer has served the U.S. Navy and Marine Corps well for over a decade.

Turbine engines are generally available over the 100 horsepower size, have the highest power to weight ratio of the fossil fueled engine types and are eminently suitable for most aviation applications.

Diesel engines are generally available in higher powers but their very low power to weight ratio makes them appropriate only when factors other than weight outweigh the extreme weight disadvantage.

Aircraft Shaft Power Engines
SFC Characteristics

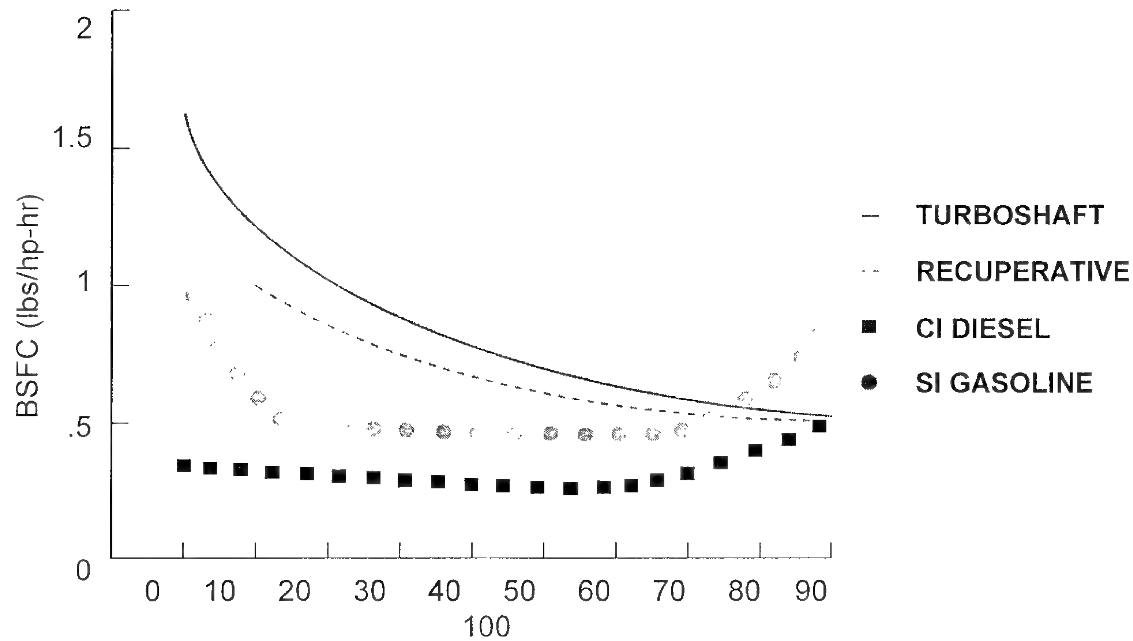


FIGURE 12

Efficiency- When engine efficiency is discussed the term SFC (Specific fuel consumption) is generally used. This term represents the quantity of fuel burned per usable engine output. Lower SFC corresponds to higher efficiency. Figure 12 shows the power versus SFC characteristics of the various types of engines discussed. Of particular note is the extremely poor SFC of the turbine at part power conditions as contrasted to the very flat part power characteristics of the SI and CI engines. For this reason, SI and CI engines are often proposed as the most appropriate solutions for the type of mission where most of the fuel is expended at part power conditions. (e.g. the common UAV mission of long loiter times to obtain data). The overall good fuel efficiency of the CI engine is attributable to its high compression ratio.

The improved efficiency of the recuperative turbine engine is attributable to the recovery of heat from the turbine exhaust. This heat is normally wasted in a shaft power turbine. The cost is an increase in weight, cost and complexity which for some applications can be a good trade. The physical arrangement and its effect on the Brayton cycle is shown diagrammatically on figure 13.

RECUPERATIVE ENGINE
BRAYTON vs. RECUPERATIVE BRAYTON CYCLE

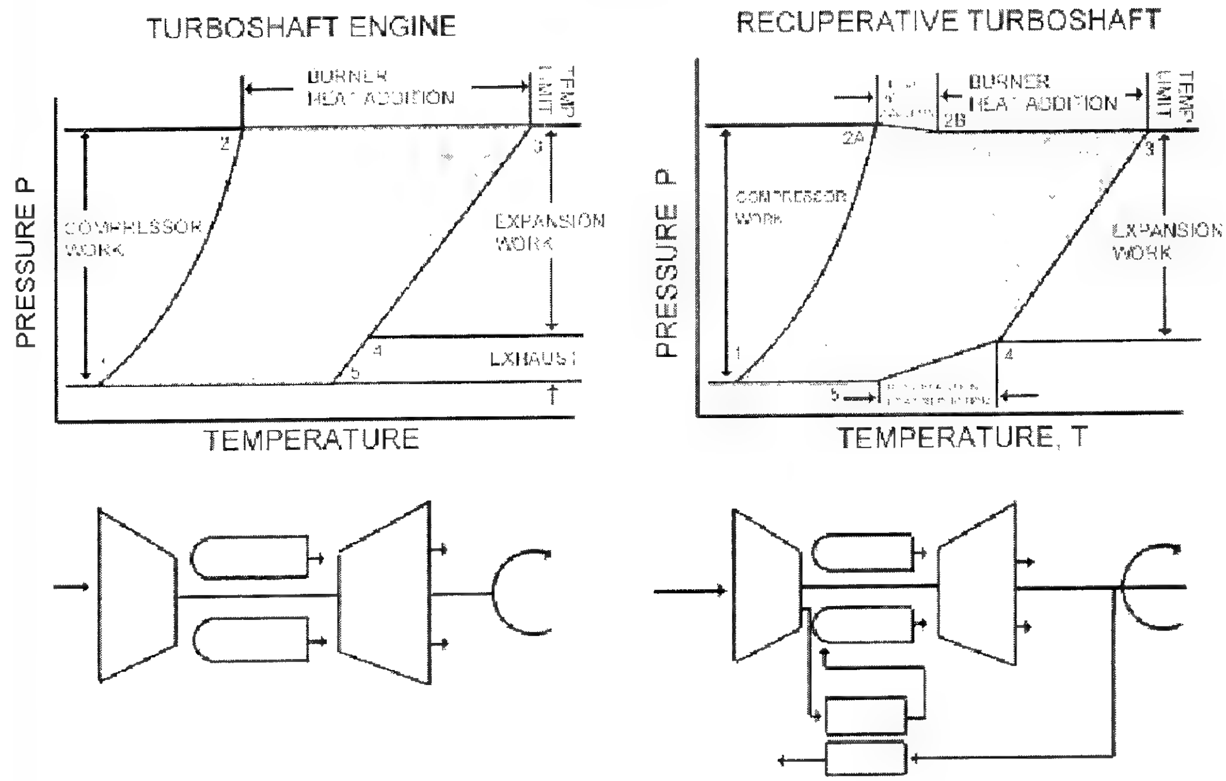


FIGURE 13

Recuperative turbine technology is not new. It is, in fact, old technology in stationary gas turbine powered electrical generators. Early on, the U.S. Navy had demonstrator engines built to study their use for long range patrol missions. The simplicity of operating with one or two engines shut down during loiter, which became standard P3 Orion practice, became the accepted solution and the aviation recuperative engine program died in the early 60's. Some tests were conducted on a small demonstrator recuperative engine at the U.S. Navy's propulsion test facility in 1994. Never have there been any studies which showed that a recuperative engine was not feasible in the 100+ horsepower class. The cost of full engineering development and production has often been the major concern. But cost should be only one of the factors in trade studies.

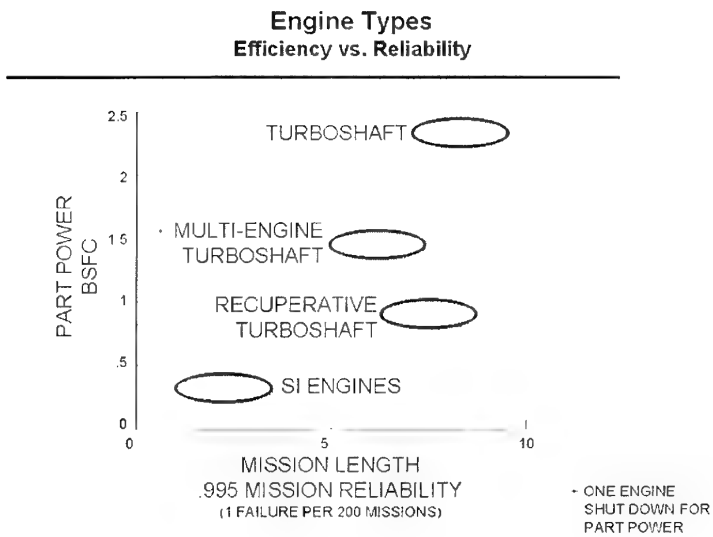
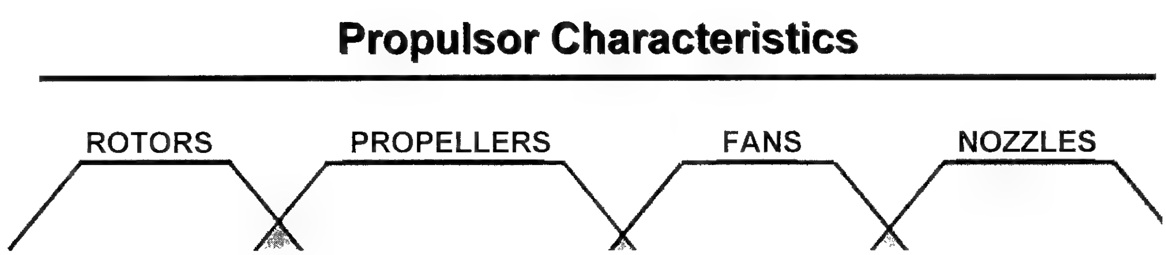


FIGURE 14

Reliability- Mission reliability is always important and is most difficult to achieve on longer missions. The longer missions require engines with very low SFC. Unfortunately engines which are characteristically the most reliable are those with the poorest SFC. This characteristic is shown on figure 14.

TRADES AND SELECTION FACTORS: All the propulsor and engine characteristics listed above become factors in the system trades and selection of a propulsion system. Attention must be given to both the propulsor and the engine component of the propulsion system. Finally the propulsion system as a package must be analyzed for its suitability to the intended application.

Propulsors- The factors used in a propulsor selection are shown in figure 15 as they relate to disk loading. It can be seen from this figure that the air vehicle flight speed, mission mix and physical configuration all affect the trades.



LOW DISK LOADING →→→→→→→→→→→→→→→→→→HIGH DISK LOADIN

Large size (diameter)	Small diameter
Low rotational speed	High rotational speed
Good Static thrust	Poor static thrust
Rapid loss of thrust with forward speed	Good thrust at higher speeds
Good propulsive efficiency at low speeds	Poor propulsive efficiency at lo speeds

FIGURE 15

Shaft Power Engine Trades

	IC	Turboshaft	Recup Turbine	Multi-Turbine
BSFC	Best	Poor	Best	Best
Weight	Poor	Best	Best	Fair
Volume	Poor	Best	Poor	Best
Reliability	Poor	Best	Best	Best
Durability	Poor	Best	Best	Best
Cost	Lowest	High	High	Highest
Notes	1	2	2,3	2,4

1 - Smaller sizes require gasoline fuel
2 - Requires gearbox for propeller
3 - Limited aviation experience
4 - Based on P3 Orion experience

FIGURE 16

Engines- Figure 16 shows a summation of the engine attributes which could be the subject of trades in selection of the engine portion of the propulsion system. No one engine is perfect for all applications and for any single application compromises must be accepted in order to achieve the *necessary* mission requirements.

Propulsion System- The trade studies on the propulsors and engines is not complete until the propulsion system as a whole is considered. If, for example, a gas turbine is selected as a prime mover, the low rotational speed required by a low disk loading propeller could lead to the need for a reduction gearbox. The increase in weight and complexity of a reduction gearbox could negate all the efficiency advantages of the low disc loading device. A moderate disc loading fan may be an appropriate choice even though mission requirements may seem to indicate a propeller is the most **efficient** solution. The fuel savings achieved with the more efficient device may all be negated by the increased weight (and therefore drag) of the complete air vehicle.

SUMMARY: We have shown that UAVs can, for propulsion purposes, be divided into five categories. Each category has its unique propulsion needs. The five categories of UAVs are well served by the variation in characteristics of the many types of propulsion systems available.

Full advantage of the broad variation of propulsion characteristics can only be achieved with early propulsion trade studies and propulsion system testing to determine and verify the optimum system configuration.

MicroFlyers and Aerial Robots
Missions and Design Criteria

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Summary
This paper provides an overview of the issues surrounding the design and choice of appropriate missions for a new class of unmanned flying vehicles known as MicroFlyers, Micro Air Vehicles, and Aerial Robots. These terms are often used interchangeably to refer to small flying machines varying from what amounts to "intelligent dust" up to vehicles in the size range of small radio-controlled models (i.e., having a typical maximum dimension of one meter). Because of the size of this class of air vehicle, it can engage in missions that are non-traditional, such as indoor flight through confined spaces, or en mass, to overwhelm a target in swarms. Also because of size, many of these vehicles will have to be autonomous. In some cases, the design of the vehicle will benefit from biological mimicry wherein the behavioral and locomotive techniques used by birds and insects will be of advantage. However, the small size of these air vehicles will also constrain them in the physical environment in much the same way that insects are not necessarily free to navigate at will in the presence of wind and precipitation.

NOMENCLATURE

Aerial Robot	*Intelligent, Autonomous UAV*
Entomopter	*Insect-Like Biomimetic Aerial Robot*
MAR	*Mesoscaled Aerial Robot*
MAV	*Small (<15 cm) UAV or RPV*
MicroFlyer	*Small (<20 cm) Aerial Robot*
MEMS	*Microelectromechanical Systems*
RCM	*Reciprocating Chemical Muscle*
RPA	*Remotely Piloted Aircraft*
RPV	*Remotely Piloted Vehicle*
UAV	*Unmanned Aerial Vehicle*

Autonomous Navigation
Not all unmanned aerial vehicles need to be autonomous, but autonomy is one thing that Aerial Robots and MicroFlyers have in common. Not only must they be able to maintain stability in flight– the difficulty of which is somewhat a function of the air vehicle configuration, but they must be able to navigate. Aerial Robots, can navigate with the aid of various standards ranging from star trackers to geographical cues to man-made aids. The class of Aerial Robots known as MicroFlyers which may operate indoors, can not necessarily access these traditional standards, and without a priori knowledge of the environment, must rely on less structured approaches to self navigation.

Navigation is the process by which one determines the best route from one location (often one's present position) to another location. The easiest method for navigating about one's environment involves moving between line-of-sight landmarks or by following paths (such as rivers) which are known to lead to the desired location. When moving through unknown territory, or regions devoid of stationary landmarks, these techniques fail and specialized tools must be employed to find one's way. Navigation tools relying upon the relative position of celestial bodies or the direction of a load stone-magnetized iron sliver floating on water provided early travelers with the ability to maintain a course over long distances. In time, sophisticated artificial land marks capable of being sensed electronically allowed the traveler to circumnavigate the globe regardless of the time of day and under all weather conditions.

Modern navigation tools use man-made constellations of ground or space-based standards which emit electromagnetic waves of known frequency, phase,

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or encoding to provide a local receiving device anywhere in the world with an estimate of its position relative to these standards. Depending upon the system configuration, coordinates on or above the Earth's surface can be determined within centimeters of the actual position. In general, these systems rely on the ability to accurately measure qualities of signals emitted from at least three sources of known position. The accuracy of the triangulated position solution is also a function of geometry, with the most accurate solutions being derived from signal sources surrounding one's current position (as opposed to signals received from sources along a line).

Some of the popular ground-based systems currently in use are VOR (**V**ery High Frequency **O**mni **R**ange) used predominantly for regional aircraft navigation, and LORAN (**Lo**ng **Ra**nge **N**avigation) which is used by both ships and planes globally. Many such systems have been deployed over the years as aids to navigation, but with the advent of the highly accurate space-based Global Positioning System (GPS), more of these ground-based systems are being decommissioned (e.g., OMEGA).

Autonomous Navigation

There are some scenarios in which the classical navigation aids are not readily available either because their signals can not be received, or because the triangulation calculations used to compute a position contain too great an error to be of use. Even if the navigation aids are available and meaningful results can be obtained, absence of human input to the navigation process can be challenging. Consider the following actual examples.

A Mars probe lands in the caldera of the Solar System's largest volcano, Olympus Mons. Scientists wish to have the probe map the caldera by deploying a small aerial robot that will fly a grid pattern across the base of the caldera while taking photographs at the grid intersections. How will the aerial robot know where it is? The magnetic field of Mars is very weak, there is no ground-based or orbital standard emitting signals by which to triangulate a position, the terrain is unfamiliar and precludes the use of landmarks.

A second example would be a MicroFlyer operating inside a building. Though GPS signals are available just outside the building— perhaps only feet away, the signal is effectively blocked by the materials used in the construction of the walls and ceiling. Compounding matters, the MicroFlyer is a flapping wing design mimicking insect locomotion and has a maximum dimension of only 12.7 centimeters (5 inches) and a weight of 50 grams (1.76 ounces) [see, http://avdil.gtri.gatech.edu/RCM/RCM/Entomopter/EntomopterProject.html]. The wavelength of the GPS satellite signals would require an antenna that is as big as the entire MicroFlyer. Without a priori knowledge of the building interior, how could such a tiny reconnaissance vehicle find its target?

In both examples, such vehicles are currently under development. The first suffers from a lack a accurate navigation aids while in the second case, though navigation signals are present and adequate, they are unable to be detected due to occlusion and the inability of a receiving antenna to be scaled to a size and weight that is compatible with this specialized vehicle. Both example vehicles are candidates for autonomous navigation.

Autonomous navigation means that a vehicle is able to plan its path and execute its plan without human intervention. In some cases, remote navigation aids can be used to help in the planning process, while at other times, the only information available to compute a path is based on input from sensors that are local to the vehicle itself. An autonomous robot is one which can not only maintain its own stability as it moves, but can also plan its movements. Autonomous robots use navigation aids when possible, but can also rely on vision, auditory, and olfactory cues. Once basic position information is gathered in the form of triangulated signals or environmental perception, machine intelligence must be applied to translate some basic motivation (reason for leaving the present position) into a route and motion plan. This plan may have to accommodate the estimated or communicated intentions of other autonomous robots in order to prevent collisions, while considering the dynamics of its own movement envelope.

Basic Principles of Autonomous Navigation

Autonomous navigation is advantageous for some mobile robotic missions— it is essential for others. In some cases, the presence of a manned vehicle is a liability because regard for life precludes engagement in missions that are lethal. Flying into nuclear contaminated areas to make measurements is one example of a mission that is better left to an unmanned system. Even the presence of a man-in-the-

loop is often a disadvantage. Remotely piloted reconnaissance vehicles that are flown by means of a ground pilot and a command/data link are susceptible to jamming, deception, or being overridden by the enemy. An autonomous vehicle requires no command links and therefore is unstoppable by jamming or overriding, and the ground pilot can not be deceived by modifying the feedback information to that is normally returned by a data link. Autonomous vehicles are superior for many tasks but the challenge to make the vehicle navigationally robust in all situations, is formidable.

For an autonomous vehicle to be navigationally robust it must be capable of six things:

1) It must have a mission goal (motivation to move),
2) It must be able to perceive its environment (for obstacle avoidance),
3) It must understand where it is presently located,
4) It must plan a path that will allow it to achieve its goal,
5) It must be self actuating (able to move), and additionally,
6) as situations change, it must be able to replan as it moves.

Sensors for Autonomous Localization and Navigation

Before an autonomous vehicle can intelligently plan a path to its goal, it must either have a stored map of its world, or it must create one as it moves based on what it perceives. In the case of the autonomous insect-like MicroFlyer, a map of the interior of the building in which it will fly would be of significant use, but even with such a map stored onboard, furniture and other unbriefed threats to the vehicle could block its path. In most cases, such a map will not be available and the MicroFlyer would have to sense the path to its target based upon other cues.

Knowing What is Up

In most systems, particularly those used in flying robots, it is critical to know where "up" is. In an aerial robot, knowing the orientation of the vertical gravity vector allows the vehicle to remain in flight parallel to the surface of the Earth, or to return to that orientation after completing a maneuver. Knowing where "up" is can also affect the calibration of various onboard sensors. Accelerometers are affected not only by changes in robot velocity but also by orientation relative to the gravity force vector which must be factored out of any measurements. Similarly, magnetometers used to determine heading rely on the measurement of only the horizontal component of the Earth's magnetic field vector. If an aerial robot with electronic compass such as a flux gate magnetometer banks in a turn so that the compass tilts relative to a plane that is tangent to the Earth's mean surface, the compass will begin to read not only the horizontal component of the Earth's magnetic field, but also part of the vertical component. In the northern hemisphere, this will result in an erroneous heading that is biased to the North. The magnetic field of the Earth can be resolved for any vehicle attitude by using three redundant magnetometers in an orthogonal array, but in order to select only the horizontal component of this vector, some knowledge of "up" is necessary to determine where the horizontal plane lies.

"Up" can be measured by a pendulum, and electronic pendulums comprised of accelerometer arrays do exist. However these are not reliable on a moving platform. An aerial robot capable of performing a coordinated banking turn would temporarily create artificial gravity due to centrifugal "force" and a pendulum would indicate that the vehicle is still flying straight and level. For this reason vertical gyroscopes are often used to remember where "up" is. A vertical gyroscope is gimballed to allow its spin axis to freely rotate about its spin center. As such, a vertical gyroscope can indicate offsets in yaw, roll, and pitch relative to its calibrated starting position if placed at the center of rotation (often the center of gravity) of an autonomous aerial robot. This starting position is usually the vertical gravity vector as derived from a pendulum sensor when the vehicle is at rest. Unlike the pendulum however, a properly placed vertical gyroscope is not affected by centrifugal "force".

Vertical gyroscopes can be simulated by twice integrating the output from orthogonal accelerometers, or from a single integration of orthogonal rate gyro outputs. Relatively accurate vertical gyroscopes can thus be created by integrating the output of orthogonal laser ring (rate) gyros.

Detecting "up" is one of the most important abilities exhibited by autonomous terrestrial robots, and is likewise one of the most difficult quantities to obtain. Once "up" has been determined, cumulative errors eventually corrupt the robot's notion of where "up" actually is. Vertical gyroscopes exhibit very good accuracy in the short term, but are subject to

drift. For this reason sensors with good long term stability but lower update rate are often coupled with vertical gyroscopes to periodically recalibrate them. For example, GPS position fixes can be very accurate but update rates from 1 to 10 Hz are too slow to meet the needs of autonomous robots engaging in high rate-of-change maneuvers. However, GPS position updates can be used to correct angular drift errors occurring in otherwise highly responsive vertical gyroscope systems. This synergy provides sufficiently accurate high bandwidth feedback for an autonomous control system to direct the dynamic envelope of most mobile robotic platforms.

Route and Motion Planning

If a global map is available, an autonomous vehicle can plan its entire route from its present position to its goal. Some route planners search for the optimum path based on rules which attempt to minimize transit time, fuel consumption, threat exposure, or other factors. Thousands of routes are planned based on way points, and the one best conforming to the mission rules is chosen. As the path is executed, unbriefed threats which would cause the autonomous vehicle to violate the mission rules may be encountered and the route must be recomputed from the vehicle's current position. Under some circumstances no solution is possible in which case certain rules must be relaxed. For example, a higher degree of threat exposure may be acceptable, however other rules may be inviolate such as those concerning mission endurance. A route requiring the vehicle to exceed its remaining fuel allotment is obviously an unacceptable alternative. Therefore, unless the robot is expendable, provision must be made for autonomous vehicle to abort its mission and return home.

A more rigorous case is one in which no global map is available. In this case, the optimum route can not be predicted, and a combination of dead reckoning and seek/avoid behaviors must be used. Dead reckoning uses time-in-motion at a certain speed along a given heading to extrapolate a new position based on a known starting point. Odometry is a form of dead reckoning often used in factory robots to count the revolutions of a drive wheel of known circumference in order to determine distance traveled independent of time. Visual odometry is also possible from aerial robots in which the passage of objects on the ground is noted. By knowing the altitude of the aerial robot and the field of view of its vision sensor, a measure of distance traveled can be deduced.

Dead reckoning is plagued by cumulative errors which arise from inaccuracies in the measurement of time, speed, and heading. These may be due to the inherent resolution of the sensors used, or my be due to drift caused by unpredictable changes in the environment. Dead reckoning errors grow as the mission progresses unless there is some standard to periodically recalibrate the absolute position of the vehicle. Dead reckoning sensors include devices such as accelerometers (to measure acceleration), rate gyroscopes (to measure rate of change of velocity), and magnetometers (to measure heading). By integrating acceleration, one can determine velocity, and by integrating velocity, one can determine position. The use of laser ring gyroscopes or accelerometers based on microelectromechanical systems (MEMS) components can increase the accuracy of dead reckoning systems.

Seek/avoid systems on the other hand, are as accurate as the resolution of the sensors used to seek the goal. Unlike dead reckoning, accuracy improves as the seeking sensor is brought nearer to its goal because the error signals provided by the sensor are greater for smaller vehicle heading deviations when near the target than when far from it. Larger error signals are less susceptible to noise, and the heading can be maintained more accurately.

The avoidance signal serves as a warning to override the seeking behavior when a threat to the vehicle is encountered. After successfully diverting from the desired seeker path by changing heading or altitude to avoid a detected obstacle by means of a preprogrammed (reflexive) or calculated (cognitive) maneuver, the avoidance sensors no longer detect the obstacle and control is returned to the seeking sensors whereupon the robot continues toward its goal on a new path.

Consider a mission in which a tiny autonomous air vehicle is launched through an air vent from the outside to search for the location of hostages being held somewhere in an abandoned building. In this example, no recent map of the interior is available, though intelligence reports indicate that the building has a group of central rooms accessible by hallways off of a main corridor. In this case a reasonable sensor suite would include ranging devices to avoid obstacles in front of, and to the sides of the vehicle. In addition a downward looking ranging device would provide altimetry information.

These could be active radio frequency, optical, or acoustic transceivers similar to radar or sonar and would only serve to keep the vehicle out of harm's way during its ingress.

Another kind of sensor would be used to provide motivation. This might be an "electronic nose" which detects small quantities of molecular species that indicate the presence of human beings. Pheromones, ammonia, or other chemicals given off by humans could be used as a cue to lead the autonomous vehicle toward its goal in much the same way that a blood hound seeks a target based on smell. A pair of molecular sensors placed on either side the MicroFlyer's "head" could then indicate that concentration of the target molecules is greater to the right, left, or if equal— straight ahead. Thus, a motivation to move in a particular direction is provided.

The MicroFlyer Mission

Given that a UAV can be made to fly stably, and autonomously navigate, where might such a device be used? Many missions for MicroFlyers have been proffered, but all basically fall into the categories of "outdoor", "urban", and "indoor". The domain for MicroFlyers will be as key elements of indoor missions. Major, and perhaps insurmountable obstacles confront MicroFlyers that fall prey to the forces of the environment. Wind and rain can prevent outdoor MicroFlyer flight from taking place as the tiny air vehicle could expend its entire energy store getting nowhere in an attempt to fly at 20 kph in a 20 kph head wind. Similarly, rain will not only attenuate signals from the necessarily high frequency command links but may even push the tiny craft to the ground. Besides, assets exist for most outdoor reconnaissance missions– why use a MicroFlyer?

Proponents would argue that MicroFlyers put the reconnaissance potential in the hands of the users that need specific information in a timely manner. Perhaps a better solution would be to invest in networked communications systems that can get the same information to the foot soldier in a timely manner from existing unmanned aerial vehicle (UAV) assets such as Predator or the Global Hawk. Global Hawk will look over *all* hills in the theater of war, providing continuous 0.09 square meter (1 square ft) resolution views of the ground from an altitude of 20 km (65,000 ft) for periods of up to 36 hours! Multiplexing the Global Hawk sensors to take snap shots of specific regions of the battlefield and to deliver them to individual users on the ground in near real time is probably an easier and better integrated approach to C^3I than the anarchy of hundreds of tiny personal eyes in the sky careening at the mercy of the wind.

Urban settings, where the next generation of conflicts are predicted to occur, present difficulty for existing UAV assets. This is because most UAVs are fixed wing vehicles and are too fast to negotiate the urban canyons. Flying high over a city is of use, but if one could gather reconnaissance down in these urban canyons– between buildings, then a greater situational awareness could be had. MicroFlyers are a reasonable candidate for this mission since they are smaller and potentially slower than conventional UAVs. Even fixed wing MicroFlyers could conceivably negotiate city streets, but MicroFlyers capable of slow flight and even hover would afford the ability to stop, look into windows, or even land in tight spaces to place sensors. On the other hand, wind and rain will still plague these tiny air vehicles, and the occlusion of signals by buildings will exacerbate communication and navigation.

The real mission niche for MicroFlyers will be indoors where the environment is controlled, and there are *no* existing airborne reconnaissance craft that can negotiate hallways, crawl under doors, or navigate ventilation systems in an attempt to complete a reconnaissance mission. It is the indoor mission that will ultimately justify the development expense. The very nature of an indoor mission will necessitate (1) multimode vehicles (flying/crawling/rolling), and (2) autonomous navigation. These two features of an indoor MicroFlyer are not absolutely necessary for outdoor missions, but outdoor MicroFlyer missions are themselves not absolutely necessary. Therefore, investment in the design of autonomous multimode MicroFlyers which incorporate these features from the inception of their design is paramount.

Morphology of a MicroFlyer

Nothing in creation exhibits fixed wing flight behavior or propeller-driven thrust. Everything that maintains sustained flight, uses flapping wings. Even though there has been considerable analysis in the literature of mechanisms for bird flight (Ellington[1], 1984) and insect flight (e.g., Azuma[2], 1992, and Brodsky[3], 1994), and ornithopter-based (bird flight) machines have been demonstrated–

nothing at the size level of an entomopter (GK: *en*, in + *temnein*, to cut (in ref. to an insect's segmented body) + *pteron*, wing → "insect wing") has been tried.

An entomopter, or robotic insect, capable of self navigating indoor flight and ground locomotion using a "reciprocating chemical muscle" technique is currently under development by a team of U.S. and European researchers[4] with funding from the U.S. Defense Advanced Research Projects Agency (DARPA). This particular MicroFlyer is referred to as a Mesoscaled Aerial Robot (MAR).

Major Hurdles

Beyond the challenges of low Reynolds number aerodynamics (*inertial force of body ÷ viscous force of air*), three major system-specific technological areas must be addressed before a any practical MicroFlyer can be fielded. These are:

- NONSCALING ITEMS
- STORED ENERGY
- PROPULSION

NONSCALING ITEMS may be functions of external factors such as established GPS frequencies over which there is little control. For example antennas may be of suboptimal gain or directivity in order to fit the form factor of a MicroFlyer, while ground station frequencies may of necessity, preclude anything but line-of-sight operation. A reconnaissance MicroFlyer operating line-of-sight at a distance of several kilometers may require an operational altitude of several thousand feet in order to clear tree lines, hills, and cultural items. The cost of being small becomes of questionable benefit when the mission envelope begins to overlap that of existing assets which can perform the same reconnaissance mission.

STORED ENERGY becomes a significant impediment as MicroFlyer mission duration increases. The present state-of-the-art in battery technology does not allow for long endurance MicroFlyer missions, though it is hoped that someday improved electrical storage media (carbon-air, fuel cells, etc.) will result in the energy densities required for useful long endurance (> 1 hour) missions in MicroFlyer-sized vehicles. Near term solutions to onboard energy storage will come from chemical or fossil fuels because of their superior energy density. As a point of comparison, consider the amount of releasable energy stored in a drop of gasoline compared to that which can be stored in a battery the size of a drop of gasoline.

Given that a high energy fuel source is used, the third system-specific technological area which must be addressed is PROPULSION, that is, how one converts the fuel's stored energy into useful, controllable work. This involves some sort of engine, and a propulsor system. The approach described in this paper is to use a chemical fuel source driving a specialized scalable engine known as the "reciprocating chemical muscle" (RCM), coupled to flapping wing propulsors. This combination is deemed to be optimal for indoor MicroFlyer missions where the MicroFlyer is more than a simple flying machine, but a robot capable of demonstrating various insect-like behaviors including the ability to land, crawl, and take off again.

Models for Beginning a MicroFlyer Design

Beyond the fact that every living thing capable of sentient navigation employs flapping wings for sustained aerial locomotion, certain features of flapping wing flight make it attractive for those missions in which MicroFlyers are believed to have the greatest potential.

Why Flapping Wing Flight?

If the most justifiable missions for MicroFlyers are indoors, then a vehicle must be optimized to negotiate constricted spaces that are bounded on all sides, land and take off with minimal ground roll, and circumvent obstacles (e.g., doors). Fixed wing solutions are immediately discounted because they require either high forward speed, large wings, or a method for creating circulation over the wings in the absence of fuselage translation.

High speed is not conducive to indoor operations because it results in reduced reaction time, especially when autonomously navigating through unbriefed corridors or amid obstacles. When indoors, slower is better.

If, on the other hand, the wings are enlarged to decrease wing loading to accommodate slower flight, the vehicle soon loses its distinction as a "micro" air vehicle. Current wisdom defines a micro air vehicle as having no dimension greater than 15 cm. Even at this scale, the forward speed required for a fixed wing vehicle to efficiently stay aloft violates the criteria for negotiating constricted spaces..

Finally, there are methods for creating circulation over the wings in the absence of fuselage translation. This can be done by "blowing" the surfaces of the wing to

increase lift in an intelligent manner by using an internally-generated pressure source. This has been demonstrated in manned aircraft and certain experimental unmanned vehicles, but is typically inefficient unless there is a source of gas pressure already available (such as bleed air from a gas turbine engine).

Another way to move air over a wing without fuselage translation is to move the wing relative to the fuselage and the surrounding air. This can be a circular motion as in a helicopter rotor, or it can be a reciprocating motion as in a flapping wing. Both serve to create a relative wind over an airfoil thereby creating lift.

A rotor is mechanically simple to spin, but does not use all parts of the wing (rotor) with the same efficiency since the inner section near the rotor hub moves more slowly than the tip. The same thing can be said for a flapping wing where the greatest relative wind is created at the wing tip, and none at the root.

A significant advantage of a flapping wing over a rotor is the rigidity of the wider chord wing relative to the high aspect ratio of a narrow rotor blade, and the fact that it can be fixed relative to the fuselage (e.g., nonflapping glide) to reclaim potential energy more efficiently than an autorotating rotor.

It could also be argued that a flapping wing implementation is an inherently lower bandwidth system than one using a helicopter rotor. Both systems require cyclic (once-per-flap or once-per-revolution) control inputs to maintain vertical lift and stability, but the frequencies at which these inputs must be generated can be much lower for comparably sized flapping implementations.

There is also a stealth advantage of a flapping implementation over a comparably sized rotor design in that the acoustic signature will be less because the average audible energy imparted to the surrounding air by the beating wing is much less than that of a rotor. The amplitude of vortices shed from the tips of the beating wing grows, and then diminishes to zero as the wing goes through its cyclical beat, whereas the rotor tip vortices (which are the primary high frequency sound generator) are constant and of higher local energy. The sound spectrum of a flapping wing will be distributed over a wider frequency band with less energy occurring at any particular frequency, thereby making it less noticeable to the human ear. All the energy of the rotor spectrum will be concentrated in a narrow band that is proportional to the constant rotor tip velocity.

As the diameter of a rotor system decreases with the size of the air vehicle design, it will become less efficient since the velocity at the tips will decrease while the useless center portion becomes a larger percentage of the entire rotor disk. To compensate for this, the designer will tend to increase the rotation frequency of the rotor to maintain lift for a given fuselage mass and power source. The increased rotation frequency will increase the frequency and energy content of the sound produced.

On the other hand, as the wing span of a flapping wing system is decreased, wing beat frequency must similarly be increased to maintain lift for a given fuselage mass, but the spectrum of the sound produced will simply broaden with more energy occurring at higher frequencies. Though the work produced to lift the fuselage mass may be the same as that for the rotorcraft, the energy will be expended over a wider acoustic bandwidth, but unlike the rotorcraft, it will be nonuniformly distributed in the horizontal plane. The net result is that a any flapping wing approach will be less noticeable than a rotary wing approach because the sound spectrum produced will approximate wide band white noise rather than a discrete tone.

The flapping wing is conducive to slow flight and even hover. It allows for short take off and landing, and may have advantages over other techniques in terms of its acoustic signature. All of these features are desirable for indoor operations, but what about circumvention of obstacles such as doors? None of the techniques mentioned so far has any particular advantage when it comes to movement through small openings such as partially-opened doors or under closed doors. Similar problems exist for small openings like windows, air vents, and pipes.

The solution is to have a multimode vehicle that is capable of not only flight, but ground locomotion. Crawling is not a particularly efficient form of locomotion if large distances must be traversed, but a machine capable of only flight is effectively neutralized were it to encounter a closed door. If a flying machine could drop to the floor and crawl the small distance necessary to go under the door, then the mission could continue.

The notion of a hovering "humming birdlike" sensor platform that darts about a room inspecting different items of interest, is constrained in the near term by the energy density of its power source. Until greater power densities can be achieved, the likely mode of operation will entail a covert quick entry to a distant area using flight, followed by a precise positioning of a sensor using ground locomotion. This may represent one percent of the overall mission duration. The remaining ninety nine percent will revolve around the operation of the emplaced sensor from its remote vantage point.

Power to Fly

The power necessary to achieve flapping flight can be calculated by using formulas derived by Azuma[2], 1992. This power is mainly a function of the following variables: vehicle mass, flapping frequency, forward speed, wing chord, wing span, and wing beat amplitude. Calculations for a slow flying flapping wing vehicle weighing 50g have been estimated (Michelson[4], 1997). Based on this analysis, just over a watt of power would be necessary to propel such an MicroFlyer. Weight reduction is the most critical factor in creating a successful MicroFlyer. The equations of flight contain terms in which weight contributes to the fourth power. Note that a doubling the MAR mass from 50g to 100g results in almost eight times the required power. For this reason it is critical that MAR structures serve multiple purposes. As an example, wings could also be antennas, legs could be inertial stabilizers in flight—perhaps someday the fuselage might even be itself a consumable fuel source!

Present State-of-the-Art in Aerial Robots

Though work is currently underway to develop fully autonomous MicroFlyers capable of indoor operations early in the 21st century using seek/avoid navigation strategies, the smallest most intelligent fully autonomous robots are currently those found in the International Aerial Robotics Competition. These aerial robots are less than 3 meters (10 feet) in any dimension and are fully autonomous. Since the inception of the competition in 1990, collegiate teams from around the world have devised autonomously navigating aerial robots capable of perceiving their environment, moving intelligently over an arena, and manipulating objects on the ground while in flight. Some of these automatons replan their routes based on the information about what they sense on the ground. A recent mission required the aerial robots to find a toxic waste dump, map the location of randomly oriented, partially buried drums, then read the labels on the drums from the air to determine the contents of each, and having done so, retrieve a sample from a particular drum. This mission was achieved in 1997 by a fully autonomous flying robot which was self navigating for nearly 20 minutes [http://avdil.gtri.gatech.edu/AUVS/IARCLaunchPoint.html].

Potential Applications

Autonomous robots will be necessary for applications which are too dull, dirty, or dangerous for human beings, or for missions which extend beyond a human life span such as space travel. These mobile robots will autonomously navigate the planet's surface, oceans, and skies without human intervention, albeit with assistance from navigation aids such as GPS which will take on greater importance as mobile robots proliferate throughout society. Future applications will include automated delivery services, continuous high altitude in situ weather measurement, service robots to maintain our living space, autonomous farming machinery, personnel transports, and of course the most effective and terrifying machines of war ever to be devised.

Prospects

Many robots exhibit levels of autonomous navigation. The simplest of which follow straight line headings to a target such as the navigation system used by the Nazis on the V1 "buzz bomb". Others are capable of autonomous preprogrammed waypoint navigation such as the Tomahawk cruise missiles used during the Gulf War of 1990. Still others like those of the International Aerial Robotics Competition are thinking machines capable of planning a route and autonomously navigating to a goal while monitoring external cues to execute en route path modifications if necessary. As the level of onboard intelligence increases with increasing computing power, the ability to navigate autonomously will become more common in mobile robots of all types. During the 21st century one should expect to see the end of teleoperated robotic control in favor of fully autonomous operation.

Conclusions

MicroFlyers are best suited to indoor missions because the environment is benign and no other assets exist to address this area of reconnaissance. Indoor operations will have to be autonomous due to

MicroFlyer size constraints that prevent it from carrying various non-scaling items such as lower frequency transmission systems. Also, command and control information can not be sent through most steel-reinforced concrete buildings with the required bandwidth to allow for teleoperation of the vehicle.

When operating autonomously indoors, MicroFlyers will have to be more than "air vehicles", they will have to be "aerial robots" capable of multimode locomotion that will include not only flight but crawling. When in flight, they will have to be able to move slow enough to negotiate winding corridors, stairwells, and narrow openings. Slow flight for unobtrusive reconnaissance missions is best done with flapping-wing propulsors.

Near term propulsion for tiny multimode robotic vehicles will be fueled from chemical or fossil fuel sources. Electrical storage density is insufficient to support slow-flight missions of reasonable endurance at this time. A reciprocating chemical muscle has been developed and tested at a macro- and milli-scale for use in a flying/crawling mechanical insect ("entomopter") referred to as a Mesoscaled Aerial Robot. The MAR uses a novel X-wing pair design that is resonantly driven by the reciprocating chemical muscle.

Empirical tests on a third generation milli-scaled reciprocating chemical muscle show that it develops sufficient force and motion to drive the wings of the MAR at frequencies necessary for flight. The characteristics of the reciprocating chemical muscle comport with those of insects, though currently at a larger "milli scale". In particular, a muscle extension/contraction range of almost 30 percent of the overall muscle length (far exceeding that of most insect muscles which are on the order of 1.5 percent) has been demonstrated at a reciprocating frequency exceeding 70 Hz and a force available of 525 grams (1.16 lbs) over the entire range of motion.

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3. Brodsky, A., *The Evolution of Insect Flight*, Oxford; New York: Oxford University Press, 1994, pp 35 - 39.

4. Michelson, R., Helmick, D., Reece, S., Amarena, C., "A Reciprocating Chemical Muscle (RCM) for Micro Air Vehicle "Entomopter" Flight," 1997 Proceedings of the Association for Unmanned Vehicle Systems, International, June 1997, pp. 429 - 435

Syllabus for
MicroFlyers and Aerial Robots
Missions and Design Criteria

Wednesday 15 September 1999

14.00 - 15.30 (1.5 hours) **MicroFlyers and Aerial Robots:** ***Missions and Design Criteria***
Prof. R. C. Michelson, Georgia Inst. of Technology, USA

AERIAL ROBOTICS

LEVELS OF AUTONOMY/INTELLIGENCE

RPV vs. UAV, is there a distinction?

Remotely Piloted
Radio-Controlled LOS Visual Feedback
No Onboard Sensory Feedback
Example: Model Airplanes

Teleoperation (virtual reality)
Onboard Real-Time Vision Sensor Feedback *(Definitely)*
Real-Time Control Force Feedback *(maybe)*
Onboard Real-Time Sound Sensor Feedback *(maybe)*
Example: Pointer

Teleoperation with Preprogrammed Flight Modes
Automated Modes
On-Board Real-time sensory feedback may be present
Example: V1 "Buzz-Bomb", Pioneer

Waypoint Navigation (Dead Reckoning)
On-Board Sensory Feedback not Necessary in Real time
Example: CL-287

Directed Autonomy (semi-autonomous)
On-Board Real-Time Sensory Feedback not Necessary at all times
Example: Mars rover, IARC vehicles

Fully Autonomous (sentient machine or biological intelligence)
On-Board Sensory Feedback Never Necessary
Example: Imperial Probe Droids, Biological UAVs
(bats and carrier pigeons)

INTERNATIONAL AERIAL ROBOTICS COMPETITION (IARC)

The Millennial Event (11:05 film)

Off-Board vs. On-Board Intelligence

Advantages of Off-Board Intelligence

LESS WEIGHT TO CARRY

- Less Power Required *(weight)*
- Longer Mission *(more fuel)*

LOWER COST AIR VEHICLE *(and System in general)*

COMPUTING POWER (beyond the state-of-the-art in miniaturization)

Advantages of On-Board Intelligence

FREEDOM FROM LINKS

- Greater Radius of Operation
- Jam Resistance
- Stealth
- Higher Degree of Interoperability
- Not Link-Bandwidth Limited
- Not link-latency Limited

QUICKER REACTION TO INTERNAL/EXTERNAL THREATS

SELF NAVIGATION

INNATE SITUATIONAL AWARENESS

15.30 - 16.00 (0.5 hours) **BREAK**

16.00 - 17.30 (1.5 hours) **MicroFlyers and Aerial Robots:** ***Missions and Design Criteria*** (continued)

Prof. R. C. Michelson

Sensors

Payloads vs. Avionics

Some Sensor Types

ATTITUDE

- Accelerometer
- Rate Gyro
- Vertical Gyro
- Ground Contact
- Magnetic and Radio Heading

POSITION

- Barometric Pressure *(Density altitude)*
- Electromagnetic Altimeters
- Pitostatic Pressure *(air speed)*
- Proximity

NAVIGATION

- Navigation Aids *(INS, DGPS, LORAN, Scene Recognition)*
- Kalman Filter Predictors
- Route Planners
- Distance Measuring Equipment

HEALTH

- Computational Integrity *(redundancy/coding)*
- Engine Health Sensors *(temp/pressure/etc.)*
- Air frame Health Sensors *(vibration/fatigue)*
- Available Energy *(fuel/battery)*
- BIT

FEEDBACK

- Actuator Position (linear/angular)
- Component RPM

MISSIONS AUTONOMOUS AERIAL ROBOTS

MILITARY/FEDERAL GOVERNMENT

Lethal

- Unstoppable Machines of War *("Terminator")*
- Aerial Mines

Nonlethal

- NBC Operations
- Hazardous Waste *(e.g., inspection/mapping/remediation)*
- Perimeter Sentry
- Reconnaissance
- Low altitude "satellite" /repeater/jammer

CIVIL

Municipal

- Traffic Surveillance
- Utilities *(e.g., power line inspection)*
- Police
- Search and Rescue
- Air quality sampling
- Low altitude "satellite" /repeater

Private

- Real Estate
- Legal/Insurance *(standoff reconnaissance)*
- Agricultural *(e.g., forestry/farming reconnaissance)*
- Package delivery *(e.g., transPacific, transarctic)*

MISSIONS SPECIFICALLY FOR AUTONOMOUS MICROFLYERS

MILITARY/FEDERAL GOVERNMENT

Lethal

- Targeted Individuals *(assassinations)*

Disruption

- Flying Swarms *(e.g., aircraft interference)*
- Clinging Swarms *(e.g., antenna blocking/mismatching)*
- Targeted equipment

Nonlethal

- Secured Perimeter Penetration
- Indoor Reconnaissance *(e.g., espionage)*
- Covert Reconnaissance
- Relay
- Covert delivery
- "Over the Next Hill Reconnaissance"??

CIVIL

Municipal

- Utilities *(e.g., inaccessible locations, nuclear plants)*
- Police
- Search and Rescue *(Oklahoma bombing, Izmit earthquake)*
- Air quality sampling *(inside smoke stacks)*

Private

- Toys
- Agricultural
- Legal/Insurance *(invasive reconnaissance)*

17.30 Conclude for Wednesday

Thursday 16 September 1999

09.00 - 10.00 (1.0 hours) **Microflyers and Aerial Robots:** ***Missions and Design Criteria*** (continued)

Prof. R. C. Michelson

MICROFLYER DESIGN CRITERIA

What are MicroFlyers or Micro Air Vehicles?

What is the *REAL* Mission for MicroFlyers?

What are the Technology Hurdles?

The "Big Three"

- Non-scaling Items
- Energy Storage and
- Propulsion

Conclusion: Navigation must be Autonomous

How to Navigate Autonomously

Indoor Flight Mechanisms

Fixed Wing?

Rotary Wing?

Flapping Wing?

Power Necessary to Fly... the beginning design point

Electrical vs. Chemical

Reciprocating Chemical Muscle

- *(RCM film)*

Weight is our Enemy!

Efficiency through Multifunctionality

DARPA Micro Air Vehicle Program Objectives *(revisited)*

DARPA Mesoscaled Aerial Robot Program Objectives

MAR Design Criteria

Innovative "Twist" on Flapping Wing Flight

- *(X-wing+Resonance+Slow Flight film)*

Innovative Flight Control Mechanism

Innovations in Wing Fabrication

10.00 Thursday Morning Lecture Concludes

For Additional Information, Consult the Following Sources:

1. **International Aerial Robotics Competition**
   .... http://avdil.gtri.gatech.edu/AUVS/IARCLaunchPoint.html
2. **Current International Aerial Robotics Competition Mission**
   .... http://avdil.gtri.gatech.edu/AUVS/CurrentIARC/FutureEventInfo.html
3. ***Dragon Stalker*** **Development**
   .... http://avdil.gtri.gatech.edu/RCM/RCM/DroneProject.html
5. **Mesoscaled Aerial Robot**
   .... http://avdil.gtri.gatech.edu/RCM/RCM/Entomopter/EntomopterProject.html
6. **About the Presenter**
   .... http://avdil.gtri.gatech.edu/RCM/RCM/MICHELSON.bio.html

MicroFlyers and Aerial Robots: ***Missions and Design Criteria***

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Aerodynamic Measurements at Low Reynolds Numbers for Fixed Wing Micro-Air Vehicles

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Summary

A description of the micro-air vehicle (MAV) concept and design requirements is presented. These vehicles are very small and therefore operate at chord Reynolds numbers below $200,000$ where very little data is available on the performance of lifting surfaces, i.e., airfoils and low aspect-ratio wings. This paper presents the results of a continuing study of the methods that can be used to obtain reliable force and moment data on thin wings in wind and water tunnels. To this end, a new platform force and moment balance, similar to an already existing balance, was designed and built to perform lift, drag and moment measurements at low Reynolds numbers. Balance characteristics and validation data are presented. Results show a good agreement between published data and data obtained with the new balance. Results for lift, drag and pitching moment about the quarter chord with the existing aerodynamic balance on a series of thin flat plates and cambered plates at low Reynolds numbers are presented. They show that the cambered plates offer better aerodynamic characteristics and performance. Moreover, it appears that the trailing-edge geometry of the wings and the turbulence intensity up to about 1% in the wind tunnel do not have a strong effect on the lift and drag for thin wings at low Reynolds numbers. However, the presence of two endplates for two-dimensional tests and one endplate for the semi-infinite tests appears to have an undesirable influence on the lift characteristics at low Reynolds numbers. The drag characteristics for thin flat-plate wings of aspect ratio greater than one do not appear to be affected by the endplates. The effect of the endplates on the drag characteristics of cambered-plate wings is still under investigation. It is known, however, that endplates do have an effect on the drag and lift characteristics of a cambered Eppler 61 airfoil/wing.

Nomenclature

Symbols

AR	full-span aspect ratio
C_D	drag coefficient (3D)
C_d	section drag coefficient (2D)
C_L	lift coefficient (3D)
C_l	section lift coefficient (2D)
C_{L_α} or C_{l_α}	lift-curve slope
$C_L^{3/2}/C_D$	endurance parameter
$C_{m/4}$	pitching moment coefficient about the quarter chord
C_{m_α}	slope of pitching moment curve
L/D	lift-to-drag ratio
M	resolution of A/D converter
Re_c or Re	root-chord Reynolds number
U_∞	freestream velocity
a	lift-curve slope
a_0	2D lift-curve slope
b	wing span
c	root-chord length
e_Q	quantization error
sAR	semi-span aspect ratio
t	wing thickness
α	angle of attack
$\alpha_{C_L=0}$	zero-lift angle of attack
α_{stall}	stall angle of attack
τ	Glauert parameter

Subscripts

max	maximum
min	minimum

Abbreviations

2D	two-dimensional (airfoil)
3D	three-dimensional (wing)
A/D	analog-to-digital
TE	trailing edge
UND-FB1	old Notre Dame aerodynamic force balance
UND-FB2	new Notre Dame aerodynamic force balance

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.

Introduction

There is a serious effort to design aircraft that are as small as possible for special, limited-duration military and civil missions. These aircraft, called micro-air vehicles (MAVs) (Davis et al, 1996; Ashley, 1998; Wilson 1998; Dornheim, 1998; Mraz, 1998; and Fulghum, 1998), are of interest because electronic surveillance and detection sensor equipment can now be miniaturized so that the entire payload mass is about 18 grams. The advantages of a MAV include compact system transportable by a single operator, rapid deployment, real-time data, low radar cross-section, difficult to see and very quiet. The potential for low production cost is also an advantage. The primary missions of interest for fixed wing MAVs include surveillance, detection, communications, and the placement of unattended sensors. Surveillance missions include video (day and night) and infrared images of battlefields (referred to as the "over the hill" problem) and urban areas (referred to as "around the corner"). These real-time images can give the number and location of opposing forces. This type of information can also be useful in hostage rescue and counter-drug operations. Because of the availability of very small sensors, detection missions include the sensing of biological agents, chemical compounds and nuclear materials (i.e., radioactivity). MAVs may also be used to improve communications in urban or other environments where full-time line of sight operations are important. The placement of acoustic sensors on the outside of a building during a hostage rescue or counter-drug operation is another possible mission.

The requirements for fixed wing MAVs cover a wide range of possible operational environments including urban, jungle, desert, maritime, mountains and arctic environments. Furthermore, MAVs must be able to perform their missions in all weather conditions (i.e., precipitation, wind shear, and gusts). Because these vehicles fly at relatively low altitudes (i.e., less than 100 m) where buildings, trees, hills, etc. may be present, a collision avoidance system is also required.

The long term goal of this project is to develop aircraft systems with a mass of less than 30 grams, have about an eight centimeter wing span that can fly for 20 to 30 minutes at between 30 and 65 km/hr. The current goal is to develop aircraft with a 15 centimeter wing span that have a mass of about 90 grams. The gross mass of micro-air vehicles and other flying objects versus Reynolds number is shown in Figure 1, with the data from Jackson (1996-97), Taylor (1969-70), and Tennekes (1996). Since it is not possible to meet all of the design requirements for a micro-air vehicle with current technology, research is proceeding on all of the system components at various government laboratories, companies and universities.

Design aims

The design requirements cover a wide range when one considers the diversity of possible applications for micro-air vehicles. The MAV must be designed as a system consisting of airframe, propulsion, payload and avionics. Although much smaller than currently operational UAVs, electrically powered MAVs will have approximately the same weight fractions, that is, 21% for the airframe, 11% for the engine, 30% for the battery, 21% for the payload, and 17% for avionics and miscellaneous items. Minimum wing area for ease of packaging and pre-launch handling is also important. Figure 2 presents the payload mass versus wingspan for MAVs and other larger UAVs.

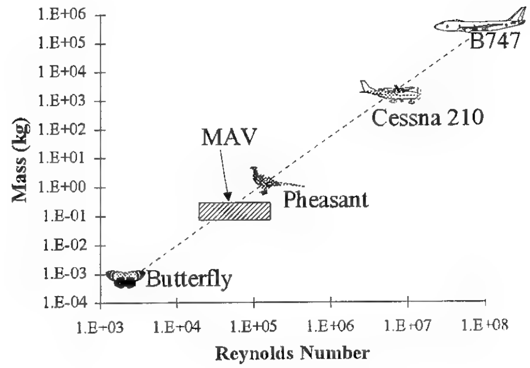


Figure 1: Reynolds number range for flight vehicles

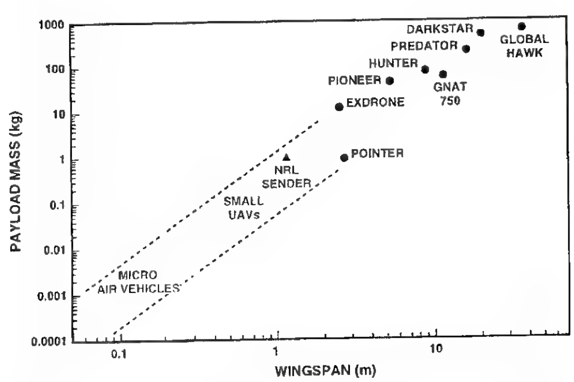


Figure 2: UAV payload vs wingspan (Davis, 1999) (Reprinted with permission of MIT Lincoln Laboratory, Lexington, Massachusetts)

A typical fixed wing MAV mission (Morris, 1997) could include the following sequence of events:

1. Launch and climb to 100 meters
2. High speed dash (64 km/hr Indicated Air Speed) to target (at 40 km/hr head wind)

3. Loiter over target area

4. Maneuver over target during loiter while turning at the minimum radius

5. Descend and climb over target area

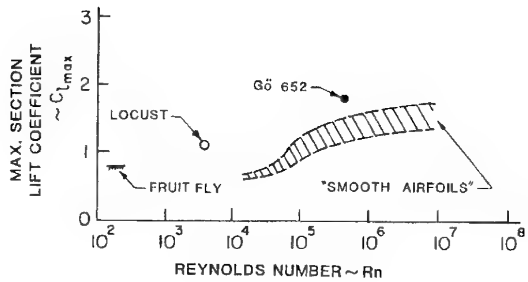
6. Climb to 100 meters

7. High speed dash ($64\,km/hr$ Indicated Air Speed) to launch point (tail wind $40\,km/hr$).

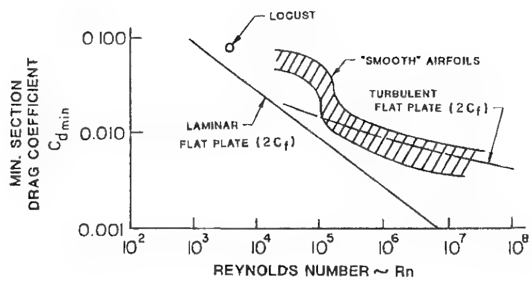
Mission constraints in this simulation include duration, operational radius, minimum turning radius, minimum climb angle, maximum altitude and number of climbs. Several MAV designs have been built and flown with this type of mission in mind. A $15\,cm$, square planform internal combustion engine powered vehicle called the Flyswatter has been flown by Morris (1997). A rudder and elevator surfaces are used to control this MAV. The first electric powered $15cm$ MAV with proportional radio control carrying a video camera was designed and flown by Matthew T. Keennon of *AeroVironment*. This vehicle called the Black Widow currently holds the record for endurance at 22 minutes (Keennon, 1999). Other MAVs with larger dimensions have been designed and flown to help develop the electronic packages and control systems (Harris, 1999; and Ailinger, 1999). Although these are examples of current vehicles, further improvements will be made when more data on low Reynolds number aerodynamics is available and smaller, more efficient electric motors and propellers have been developed.

The airfoil section and wing planform of the lifting surface occupy a central position in all design procedures for flying vehicles. Therefore, all low Reynolds number vehicles share the ultimate goal of a stable and controllable vehicle with maximum aerodynamic efficiency. Aerodynamic efficiency is defined in terms of the lift-to-drag ratio. Airfoil section $C_{l_{\max}}$, $C_{d_{\min}}$ and $(C_l/C_d)_{\max}$ as a function of Reynolds number are shown in Figures 3a, 3b, and 3c after McMasters and Henderson (1980). It is clear from this figure that airfoil performance deteriorates rapidly as the chord Reynolds number decreases below $100,000$. While the maximum lift-to-drag ratio for most low-speed fixed-wing aircraft ($U_\infty < 50\ m/s$) is greater than 10, values for insects and small birds are usually less than 10. Furthermore, to achieve these values for MAVs at low Reynolds numbers, the wings must emulate bird and insect wings and be very thin (i.e., $t/c < 0.06$) with a modest amount of camber.

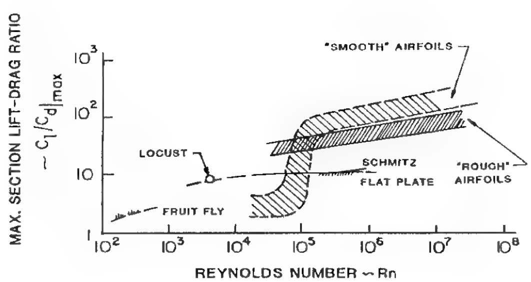
Requirements for a typical propeller driven MAV, for example, include long flight duration (i.e., high value of $C_L^{3/2}/C_D$ at speeds up to $65\,km/hr$ at chord Reynolds numbers from about $45,000$ to $180,000$ and altitudes from 30 to 100 meters). Since these vehicles are essentially small flying wings, there is a need to develop efficient low Reynolds number, low aspect-ratio wings which are not overly sensitive to wind shear, gusts, and the roughness produced by precipitation. Furthermore,



(a) Maximum lift coefficient



(b) Minimum drag coefficient



(c) Maximum lift-to-drag ratio

Figure 3: Airfoil performance (McMasters and Henderson, 1980)

confidence that the operational vehicle will perform as designed is important in all applications.

Flow problems

Although design methods developed over the past 35 years produce efficient airfoils for chord Reynolds numbers greater than about $200,000$, these methods are generally inadequate for chord Reynolds numbers below $200,000$, especially for very thin airfoils. In relation to the airfoil boundary layer, important areas of concern are the separated regions which occur near the leading and/or trailing edges and transition from laminar to turbulent flow if it occurs. It is well known that separation and transition are highly sensitive to Reynolds number, pressure gradient, and the disturbance environment. Transition and separation play a critical role in determining the development of the boundary layer which, in turn, affects the overall performance of the airfoil. The aerodynamic characteristics of the wing and other components in turn affect the static, dynamic and aeroelastic stability of the entire vehicle. Therefore the successful management of the sensitive boundary layer for a particular low Reynolds number vehicle design is critical.

The survey of low Reynolds number airfoils by Carmichael (1981), although almost two decades old, is a very useful starting point in the description of the character of the flow over airfoils over the range of Reynolds numbers of interest here. The following discussion of flow regimes from $1,000 \leq Re_c \leq 200,000$ is a modified version of Carmichael's original work.

- In the range between $1,000 \leq Re_c \leq 10,000$, the boundary layer flow is laminar and it is very difficult to cause transition to turbulent flow. The dragon fly and the house fly are among the insects that fly in this regime. The dragon fly wing has a sawtooth single surface airfoil. It has been speculated that eddies in the troughs help keep the flow from separating. The house fly wing has large numbers of fine hair-like elements projecting normal to the surface. It is speculated that these promote eddy-induced energy transfer to prevent separation. Indoor rubber-powered type model airplanes also fly in this regime. It has been found that both blunt leading and trailing edges enhance the aerodynamic performance.

- For chord Reynolds numbers between $10,000$ and $30,000$, the boundary layer is completely laminar and artificial tripping has not been successful. Experience with hand-launched glider models indicates that when the boundary layer separates it does not reattach.

- The range $30,000 \leq Re_c \leq 70,000$ is of great interest to MAV designers as well as model aircraft builders. The choice of an airfoil section is very important in this regime since relatively thick airfoils (i.e., 6% and above) can have significant hysteresis effects caused by laminar separation with transition to turbulent flow. Also below chord Reynolds numbers of about $50,000$, the free shear layer after laminar separation normally does not transition to turbulent flow in time to reattach. Near the upper end of this range, the critical Reynolds number can be decreased by using boundary layer trips. Thin airfoil sections (i.e., less than 6% thick) at the upper end of this regime can exhibit reasonable performance.

- At Reynolds numbers above $70,000$ and below $200,000$, extensive laminar flow can be obtained and therefore airfoil performance improves although the laminar separation bubble may still present a problem for a particular airfoil. Small radio controlled model airplanes fly in this range.

- Above Re_c of $200,000$, airfoil performance improves significantly and there is a great deal of experience available from large soaring birds, large radio controlled model airplanes, human powered airplanes, etc.

Laminar separation bubbles occur on the upper surface of most airfoils at Reynolds numbers above about $50,000$. These bubbles become larger as the Reynolds number decreases, usually resulting in a rapid deterioration in performance, i.e., substantial decrease in L/D. In principle the laminar separation bubble and transition can be artificially controlled by adding the proper type of disturbance at the proper location on the airfoil. Wires, tape strips, grooves, steps, grit, or bleed-through holes in the airfoil surface have all been used to have a positive influence on the boundary layer in this critical Reynolds number region. The type and location of these so-called "turbulators" and their actual effect on the airfoil boundary layer has not been well documented. Furthermore, the addition of a turbulator *does not always* improve the airfoil performance. In fact, how the disturbances produced by a given type of turbulator influence transition is not completely understood.

As a result of this critical boundary layer behavior, several important questions must be addressed:

1. What is the free stream disturbance level and flight environment for a given low Reynolds number application?

2. If the flight conditions are known and a suitable design technique was available, could the resulting vehicle or component be adequately evaluated in a wind tunnel which, in general, has a different disturbance level and environment than the flight condition?

3. Is the hysteresis in aerodynamic forces observed in low turbulence wind tunnel experiments present in powered applications (i.e., do structural vibrations originating with the propulsion or drive system affect boundary layer transition)?

4. Because the critical quantities measured in wind tunnel experiments are very small, what is the level of accuracy needed to improve design and analysis methods?

Preliminary experiments

Many of the problems plaguing very low Reynolds number research involve the difficulties associated with making accurate wind/water tunnel models and obtaining reliable data. Because the boundary layers are sensitive to small disturbances, accurate wind/water tunnel models are very important in the evaluation of a given design. Furthermore, because the forces, pressure differences and velocities are extremely small, a great deal of care must be exercised to obtain accurate and meaningful data. Low Reynolds number aerodynamic research has been in progress at the University of Notre Dame since 1978. However, chord Reynolds numbers below about $80,000$ were seldom of interest in the studies before 1996. Also, most of the studies were for relatively thick airfoils, e.g. the 11% thick Lissaman 7769, the 13% thick Miley M06-13-128, and the 13% thick Wortmann FX 63-137 airfoils. The only relatively thin airfoils studied were the Eppler 61 and Pfenninger 048 airfoils. The Eppler 61, shown in Figure 4, was originally designed for model airplanes with a chord Reynolds numbers of about $80,000$ and has a thickness of 5.63% and 6.3% camber. Figure 5 shows a schematic of the Pfenninger 048 airfoil geometry tested by Burns (see Burns, 1981). This airfoil has a thickness-to-chord ratio of 4.8% and a 4.2% camber.

Figure 4: Eppler 61 airfoil profile

Figure 5: Pfenninger 048 airfoil profile

The wind tunnel data shown in Figure 6 for the Eppler 61 and the Pfenninger 048 airfoils was obtained in 1980 and published by Burns (1981) and Mueller and Burns (1982). Figure 6 indicates that for chord Reynolds numbers below $90,000$, the thinner and sharper leading edge Pfenninger airfoil performs better than the Eppler 61 airfoil.

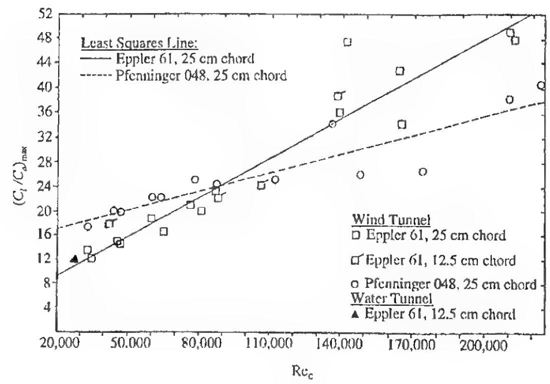


Figure 6: Maximum lift-to-drag ratio versus chord Reynolds number for the two-dimensional Eppler 61 and Pfenninger 048 airfoils (Burns, 1981)

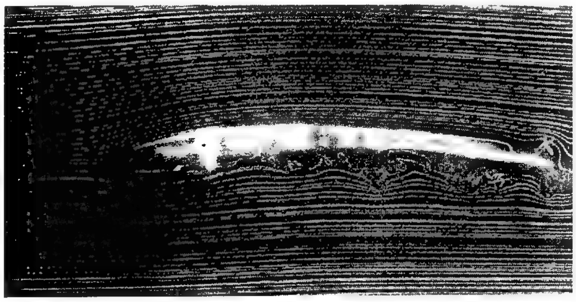
Burns also studied the flowfield over the Eppler 61 airfoil for different Reynolds numbers using the smoke wire technique. The location of the boundary layer separation could be obtained from his flow visualization photographs. Figure 7 shows the effect of changing the angle of attack on the boundary layer for $Re_c = 46,000$.

Flow visualization was also conducted on the Pfenninger 048 airfoil at different Reynolds numbers and different angles of attack. Figure 8 shows examples of the flow visualization images for $Re_c = 47,000$.

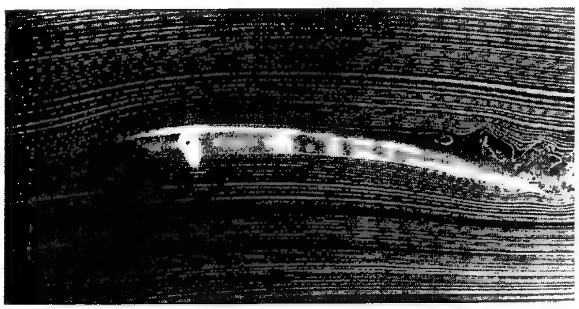
A new series of experiments was performed in the Spring of 1997 to evaluate several thin airfoil shapes using the existing strain gauge force balance (UND-FB1) in the Hessert Center water tunnel. The results for lift and drag from these experiments down to a chord Reynolds of $25,000$ were very encouraging. A more complete experimental study of one of these airfoil shapes (i.e., the Eppler 61) was performed during the summer of 1997 (Prazak and Mueller, 1997). These experiments covered the Reynolds number range from $12,000$ to $63,000$. Hydrogen bubble flow visualization was used to determine the location of boundary layer separation and the existing wind tunnel lift/drag force balance (UND-FB1) was used to make aerodynamic measurements. All of these 2D experiments included two endplates. The $(C_l/C_d)_{\max}$ for the 2D Eppler 61 from these water tunnel experiments is included in Figure 6 (▲). The results of the Prazak and Mueller study in the water tunnel indicated that by adding a computer data acquisition system to the UND-FB1 force balance, the uncertainty in the force measurements down to $Re_c = 20,000$ could be reduced significantly for the full span models.

Scope of present study

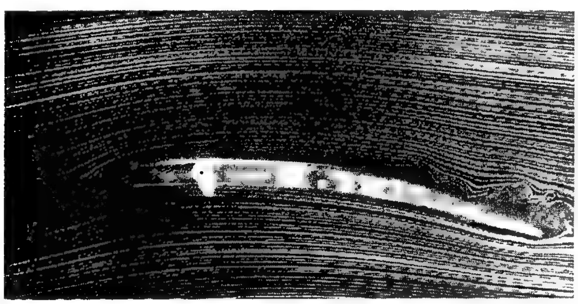
The purpose of the present work is to present and discuss the measurement problems associated with small aspect ratio wings at Reynolds numbers below $200,000$.



(a) $\alpha = 0^\circ$

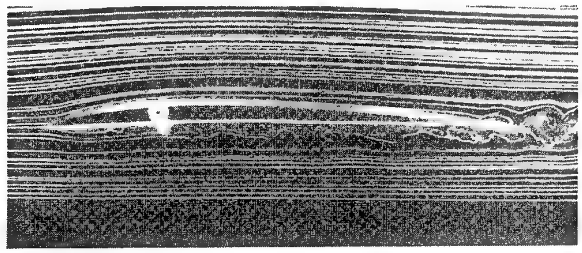


(b) $\alpha = 4^\circ$

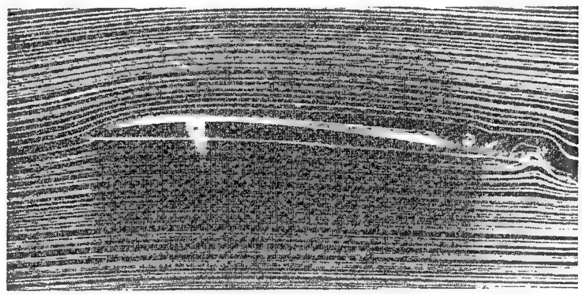


(c) $\alpha = 8^\circ$

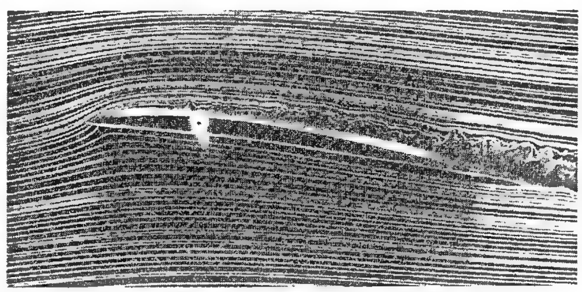
Figure 7: Smoke flow visualization on Eppler 61 airfoil at $Re_c = 46,000$ *(Burns, 1981)*



(a) $\alpha = 0^\circ$



(b) $\alpha = 4^\circ$



(c) $\alpha = 8^\circ$

Figure 8: Smoke flow visualization on Pfenninger 048 airfoil at $Re_c = 47,000$ *(Burns, 1981)*

Both wind tunnel and water tunnel experiments were performed in an attempt to acquire 2D airfoil and finite low aspect ratio wing data. Studies of the effect of two endplates on the results for 2D configurations and one endplate for semi-span or half models were also made.

Apparatus and procedures

Wind tunnel

The Hessert Center for Aerospace Research is equipped with two similar, horizontal, subsonic open-circuit wind tunnels. Each indraft tunnel has a contraction ratio of 20.6:1. The cross-sections of the entrance and test section are square. The largest test section is two feet by two feet (61 cm by 61 cm). The contraction cones are designed to provide very low turbulence levels in the test section. Just ahead of the contraction cone are twelve anti-turbulence screens. Both the contraction cone and the test sections are mounted on rollers to provide an easy means of interchanging these components. Downstream of the test section is the diffuser which is fixed into the wall of the laboratory. The diffuser decelerates the air and also gradually transforms the square contour to a circle. The impeller is driven by a variable speed electric motor. By varying the speed of the motor, the tunnel speed may reach a maximum of approximately $120 ft/sec$ ($36.6 m/s$) with a four square foot test section ($3,221\,cm^2$). The test sections used are six feet (1.82 meters) in length. All wind tunnel experiments presented in this report were conducted in one of these subsonic wind tunnels. The range of velocities required for tests up to $Re_c = 200,000$ could easily be obtained. In general, the minimum velocity for force balance measurements was kept above $5\,m/s$ ($16.4\,ft/s$). Figure 9 is a schematic of the wind tunnel used. The freestream turbulence intensity was approximately 0.05% over the range of interest.

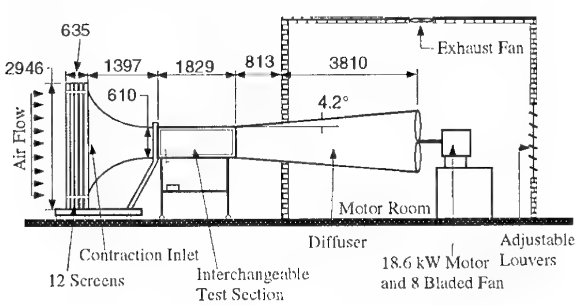


Figure 9: Schematic of the low-speed wind tunnel (all dimensions in mm)

Water tunnel

For tests between $20,000 \leq Re_c \leq 80,000$, an Eidetics® free-surface water tunnel with a $15\,in \times 18\,in$ ($38.1\,cm \times 45.7\,cm$) test section, pictured in Figure 10, was used. The water tunnel is also located in the main laboratory of the Hessert Center. Water velocities up to $1.28\ ft/sec$ ($39\ cm/sec$) can be obtained in the test section. A freestream turbulence intensity of less than 1% has been reported by the manufacturer of the water tunnel.

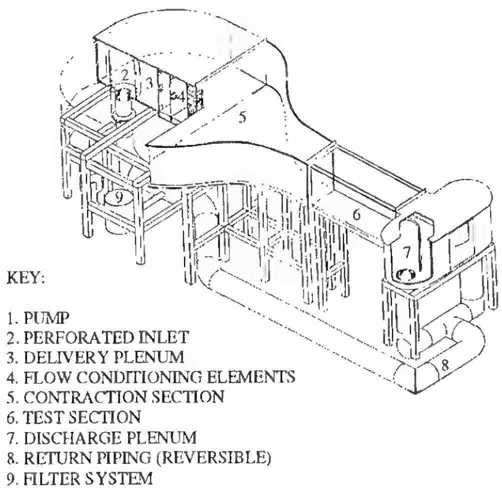


Figure 10: Schematic of the flow visualization water tunnel (Eidetics®)

Flow visualization techniques

A qualitative visual examination of the flow as it passes an airfoil is key in understanding its quantitative aerodynamic characteristics. In the wind tunnel, two different methods can be used to generate smoke for this flow visualization. With the first method, smoke is generated by a device which allows kerosene to drip onto electrically heated filaments; the smoke is then funneled to a smoke rake. The rake has a filter bag and cooling coils which reduce the smoke temperature to approximately ambient before passing through the anti-turbulence screens and into the test section. With the second method, a fine wire is placed upstream of the model. This wire is coated with oil and an electric current is applied to the wire. As the wire gets heated, the small beads of oil formed on the wire burn, which gives rise to fine smoke streaklines. This technique, which has been described in more details by Batill and Mueller (1980), is referred to as the *smoke-wire* technique. The water tunnel is excellent for flow visualization using either the hydrogen bubble or dye injection technique. A Kodak DC120 digital camera and CCD video cameras are available to capture flow visualization results.

Description of the UND-FB1 balance

Most of the results on thin plates were obtained with the existing three-component platform aerodynamic balance UND-FB1. This balance can be used to measure lift, drag and pitching moment about the vertical axis. The balance is an external balance placed on top of the test section of either of the two low-speed wind tunnels. With this balance, lift and drag forces are transmitted through the sting which is mounted directly to the moment sensor. The moment sensor is rigidly mounted to the adjustable angle of attack mechanism on the top platform. The lift platform is supported from the drag platform by two vertical plates that flex only in the lift direction. The lift and drag platforms are also connected with a flexure with bonded foil strain gauges mounted on it. The drag platform is supported by two vertical plates that flex only in the drag direction and hang from two more vertical flexible plates attached to the base platform of the balance. The base and drag platforms are also connected by a flexure with strain gauges mounted on it. For this balance a second set of flexures, for both lift and drag, are engaged when the loads are large. For the range of forces measured in this investigation, the second set of flexures was never engaged. Figure 11 shows a schematic of the old balance setup in the wind tunnel. The arrangement with two endplates shown in Figure 11 is known as arrangement number 1. Arrangement number 2, not shown, has the lower endplate removed for the semi-infinite tests.

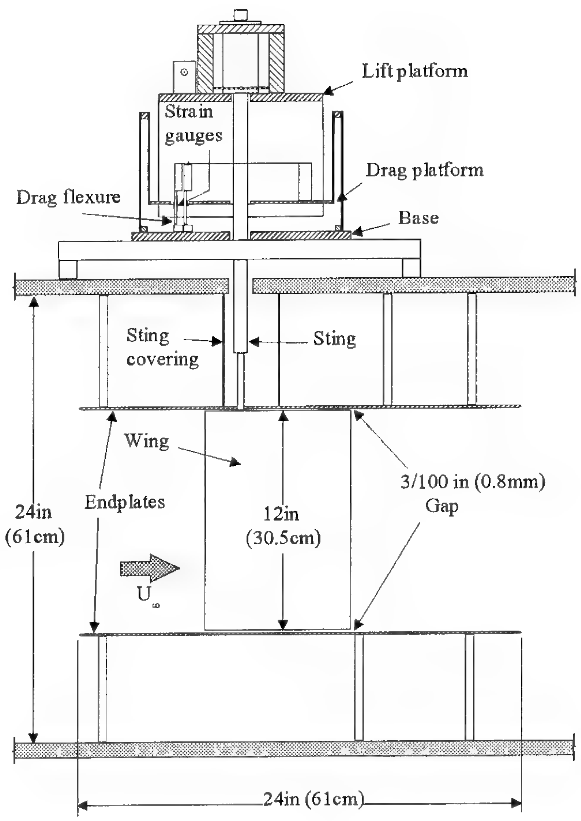


Figure 11: UND-FB1 balance arrangement (1) with two endplates in the wind tunnel

Thin-plate models for current investigation

Keeping in mind the objective of this first phase of the investigation which was to study the aerodynamic characteristics of small, low aspect-ratio flat and cambered wings, several thin, flat and cambered rectangular aluminum models with a thickness-to-chord ratio of 1.93% were built. Thin models were selected because birds and insects have very thin wings. The models either had a 5-to-1 elliptical leading edge and a 3° tapered trailing edge, or 5-to-1 elliptical leading and trailing edges. The cambered models had a circular arc shape with 4% camber. The semi-span aspect ratios (sAR) tested varied between 0.50 and 3.00. The root-chord length of the models was either $4\,in$ ($10.2\,cm$) or $8\,in$ ($20.3\,cm$). Figure 12 shows schematics of the airfoil geometries for the wings with a tapered trailing edge, while Table 1 gives the dimensions of the different models used. With the nomenclature used for the wing designation, the first four characters define the nominal dimensions of the model. For instance, C8S4 means a **C**hord of $8\,in$ and a **S**pan of $4\,in$. The following characters, if any, define the shape: a **C** means a cambered plate and **E** means an elliptical trailing edge instead of a tapered trailing edge. A maximum span of $12\,in$ ($30.5\,cm$) was chosen so that these models could be used in both the wind and water tunnels.

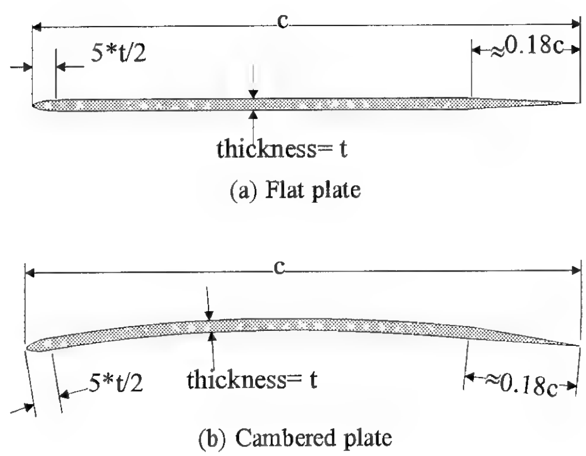


Figure 12: Airfoil geometry for models with tapered trailing edge

Designation	Chord (in)	Span (in)	sAR	Thickness (in)	Camber (%)
C8S4	7.973	3.998	0.5	0.155	0
C8S8	7.973	8.003	1.0	0.154	0
C8S12	7.985	12.01	1.5	0.157	0
C4S8	3.999	8.019	2.0	0.077	0
C4S12	4	12.014	3.0	0.077	0
C8S4C	7.975	3.995	0.5	0.156	4
C8S8C	7.983	8	1.0	0.156	4
C8S12C	7.908	12.013	1.5	0.156	4
C4S8C	3.995	8	2.0	0.078	4
C4S12C	3.936	11.998	3.0	0.079	4
C8S12E	7.969	12.011	1.5	0.156	0
C8S12CE	7.931	12.011	1.5	0.157	4

C: cambered; E: elliptical trailing edge

Table 1: Wing dimensions

Tunnel configurations

Endplates were mounted in the wind and water tunnels. The plates could be removed to simulate either a semi-infinite model or a finite model. All wings tested were held at the quarter-chord point and the sting was covered by a streamlined sting covering in the wind tunnel and a cylindrical covering in the water tunnel. The gaps between the wing and the endplates were adjusted to approximately $0.03in$ ($0.8mm$). Mueller and Burns (1982) showed that gap sizes varying between 0.1 mm and 1.4 mm are usually acceptable and do not affect the results. Furthermore, Rae and Pope (1984) suggest that the gap be less than $0.005 \times \text{span}$. For a $12in$ ($30.5cm$) span model, this corresponds to a maximum gap size of $0.06in$ (1.5 mm), which is larger than the gap used in the current investigation. All 2D tests (or infinite wing/airfoil tests) were performed with both endplates present. For semi-infinite wings (denoted by the semi-span aspect ratio symbol sAR), the bottom plate was removed. Finally, for finite wing tests (denoted by the aspect ratio symbol AR), both endplates and the sting covering were removed.

Data acquisition system with UND-FB1 balance

Signals from the strain gauges were measured with very sensitive instrumentation. The strain gauges were configured in a full Wheatstone bridge. An excitation voltage of 5 V was used for all the strain gauge bridges. The bridge signals were read with an instrumentation amplifier circuit, with available gains from 1 to 8,000. The amplified analog signals were sent to the computer where they were then converted using a four-channel, 12-bit A/D converter from *United Electronic Industries* (UEI). Four data channels (lift, drag, moment and dynamic pressure) could be measured. All the data was acquired using a PC-based data acquisition system running the LABVIEW® 5 graphical programming language. The angle of attack was controlled manually with the UND-FB1 balance.

Procedure for data acquisition

Before measuring any aerodynamic force and moment with either balance, the amplifier gains were adjusted to maximize the output signals that were expected during a given set of experiments. The balance was then calibrated using known masses. The lift, drag and moment axes were all independent.

For tests looking at the aerodynamic characteristics as a function of angle of attack, the tunnel velocity was adjusted with the model at $\alpha = 0°$ to yield the desired nominal Reynolds number. The angle of attack was then, in general, set to $\alpha = -15°$. Data was taken for angles of attack up to a large positive angle by an increment of $1°$. The wing was then brought back to $\alpha = 0°$ by an increment of $-1°$ in order to see if hysteresis was present. Offset readings were measured for all four data acquisition channels before the tunnel was turned on with the model at $\alpha = 0°$. At the end of the run, the tunnel was turned off with the model at $\alpha = 0°$ and drift readings were obtained for all channels. The offset voltage for a given channel was subtracted from all the voltage readings for that channel. A percentage of the drift was also subtracted from all the readings. A linear behavior was assumed for the drift. This means that if n angles of attack were tested with the tunnel running, $1/n \times \text{drift}$ was subtracted from the first point, $2/n \times \text{drift}$ was subtracted from the second point, and so forth. Other procedures related to specific applications will be presented in the text when appropriate.

Measurement uncertainty with balance UND-FB1

Uncertainties in the measurements were computed using the Kline-McClintock technique (Kline and McClintock, 1953) for error propagation. The two main sources of uncertainty were the quantization error and the uncertainty arising from the standard deviation of

a given mean output voltage. The quantization error is $e_Q = \frac{1}{2}\left[\frac{\text{Range in volts}}{2^M}\right]$, where M is the number of bits of the A/D converter. Optimizing the range of the output voltages can help to reduce the uncertainties. If the gain is increased, the standard deviation of the mean will also be increased, but the ratio of the standard deviation to the mean will basically remain the same. However, the uncertainty from the quantization error will be reduced because the quantization error is a fixed value (a function of the range and the resolution of the A/D converter). The ratio of the quantization error to the mean voltage will then be smaller if a larger gain is used and a larger balance output mean voltage is obtained.

The uncertainty in the angle of attack was determined to be on the order of $0.2° - 0.3°$. Figures 13 through 15 show an example of uncertainties obtained at $Re_c = 60,000$ with the cambered plates. Error bars indicate the uncertainty in C_L, C_D and $C_{m/4}$. The average uncertainties from $\alpha = 3°$ and up are approximately 6% to 7% for C_L and C_D and 10% for $C_{m/4}$.

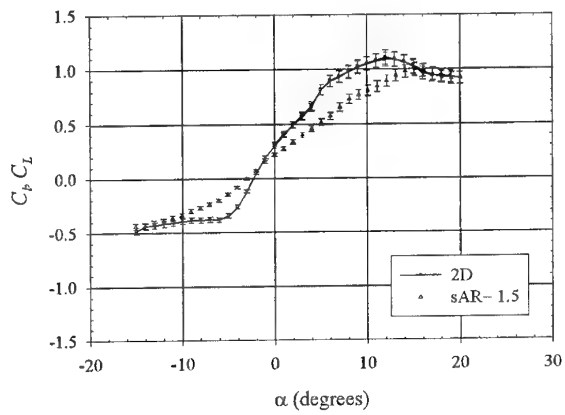


Figure 13: Uncertainties in lift coefficient for cambered plates at $Re_c = 60,000$ with UND-FB1

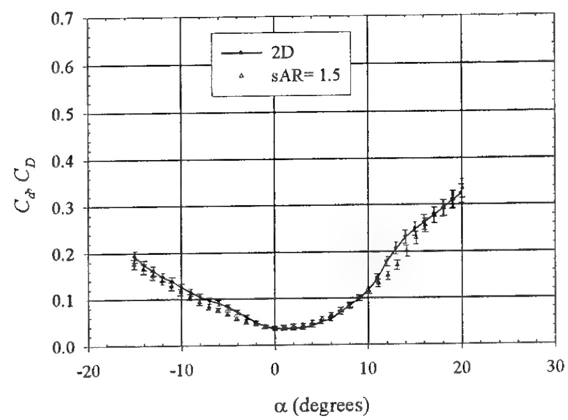


Figure 14: Uncertainties in drag coefficient for cambered plates at $Re_c = 60,000$ with UND-FB1

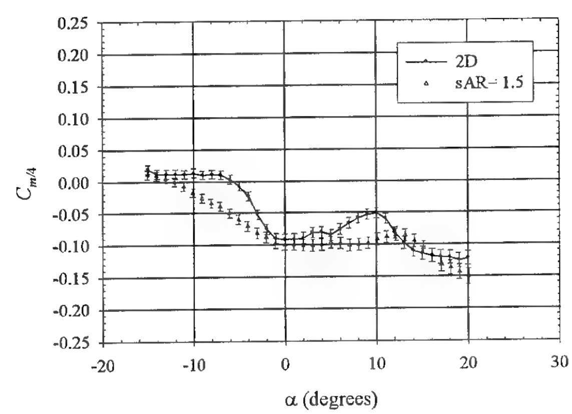


Figure 15: Uncertainties in pitching moment coefficient for cambered plates at $Re_c = 60,000$ with UND-FB1

New force/moment aerodynamic balance UND-FB2

Description

A new platform force/moment balance was designed by Matt Fasano, Professional Specialist at the Hessert Center for Aerospace Research, and built for the aerodynamic studies on low aspect-ratio wings down to chord Reynolds numbers of 20,000. The design of this new balance (UND-FB2) was based on the existing balance (UND-FB1) and measures lift, drag, and pitching moment about the vertical axis. It is an external balance placed on top of the test section for either of the two low-speed wind tunnels or the water tunnel. Due to the better sensitivity of the newly designed balance (UND-FB2), only this balance is now used with the water tunnel.

With this balance, lift and drag forces are transmitted through the sting which is mounted directly to the moment sensor (see Figure 16 for a schematic of the new balance). The moment sensor is rigidly mounted to the adjustable angle of attack mechanism on the top platform. The lift platform is supported from a platform, called the drag platform, by two vertical plates that flex only in the lift direction. The lift and drag platforms are also connected with a $1/8\,in \times 3/8\,in \times 1.5\,in$ ($3.2\,mm \times 9.5\,mm \times 38.1\,mm$) flexure with bonded foil strain gauges mounted on it. The drag platform is supported by two vertical plates that flex only in the drag direction and hang from two more vertical flexible plates attached to the base platform of the balance. The base and drag platforms are also connected by a $1/16in \times 3/8in \times 1.5in$ ($1.6mm \times 9.5mm \times 38.1mm$) flexure with strain gauges mounted on this drag flexure. Both flexures act like cantilever beams when loads are applied to the balance.

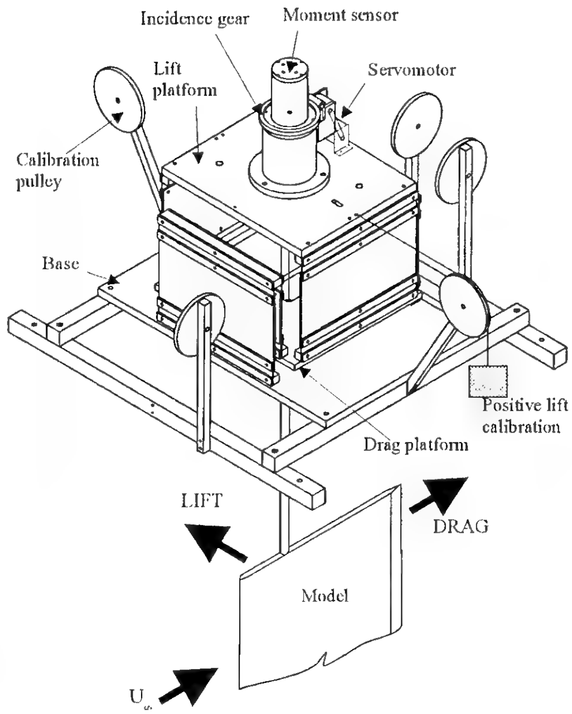


Figure 16: Schematic of the new balance UND-FB2

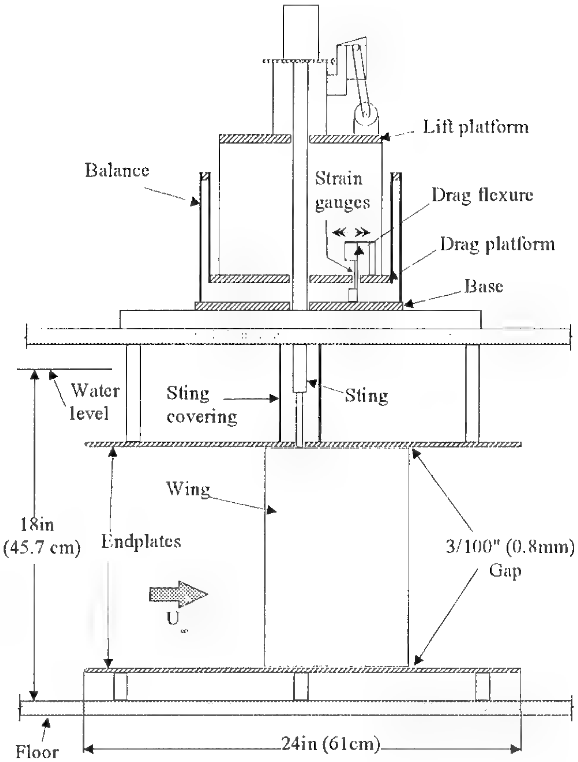


Figure 17: New-balance arrangement (1) in the water tunnel with two endplates

As mentioned earlier, endplates were mounted in both wind and water tunnels. Figure 17 shows a schematic of the new balance with the endplates in place in the water tunnel. All wings tested were held at the quarter-chord point and the sting was covered by a streamlined sting covering in the wind tunnel and a cylindrical covering in the water tunnel.

The moment sensor is a *Transducer Techniques* RTS-25 reaction torque sensor. This torque sensor uses bonded foil strain gauges and is rated at $1.5mV/V$ output. The maximum rated capacity is $25\,oz \cdot cm$ ($17.7\,N \cdot cm$) and a torsional stiffness of $1,324\,N \cdot cm/\text{rad}$. The moment sensor is attached to an adjustable angle of attack mechanism powered by a servomotor with a controller.

Electronics

Signals from the strain gauges are measured with very sensitive instrumentation. The strain gauges for the drag and lift flexures are 350 ohms with a G-factor of 2.09 and are configured in a full Wheatstone bridge. An excitation voltage of $5\,V$ is used for all the strain gauge bridges. The bridge signals are read with an instrumentation amplifier circuit with a gain as high as 8,000. Due to the sensitivity of the circuit many precautions were made to reduce noise. At first, Ni-Cd rechargeable batteries were used to power the amplifiers, analog-to-digital converters, and the excitation voltage for the strain gauges. A DC power supply is now being used because of the quick discharge of the batteries during data acquisition. The batteries used could not provide a constant voltage for several hours.

The amplifiers and analog-to-digital converters are mounted on a circuit board placed in a control box with switches and potentiometers (pots) to adjust the gains, offsets and balance the Wheatstone bridges. Four data channels (lift, drag, moment and dynamic pressure when necessary) can be measured quasi-simultaneously. The input differential signal from each channel is sent through two amplifiers from *Analog Devices*: a precision instrumentation AD624 amplifier (gain of 1, 100, 200 or 500) and a software programmable AD526 gain amplifier (gain of 1, 2, 4, 8 or 16). The amplified analog single-ended signals from the four channels are then converted to digital signals using a *Burr-Brown* AD7825, four-channel, 16-bit analog-to-digital converter. The signals are then sent to a *National Instruments* digital data acquisition card (NIDAQ) in a data acquisition computer. The amplified single-ended analog signals can also be sent directly to the computer, thus bypassing the 16-bit A/D converters; the signals are then converted using the four-channel, 12-bit A/D UEI converter, mentioned earlier. With the 16-bit A/D system, each amplifier circuit is identical except for the fourth channel where the amplifiers can be bypassed and a single-ended signal can be sent directly to the 16-bit A/D converter. Figure 18 is a simplified schematic of

the electronic circuitry used.

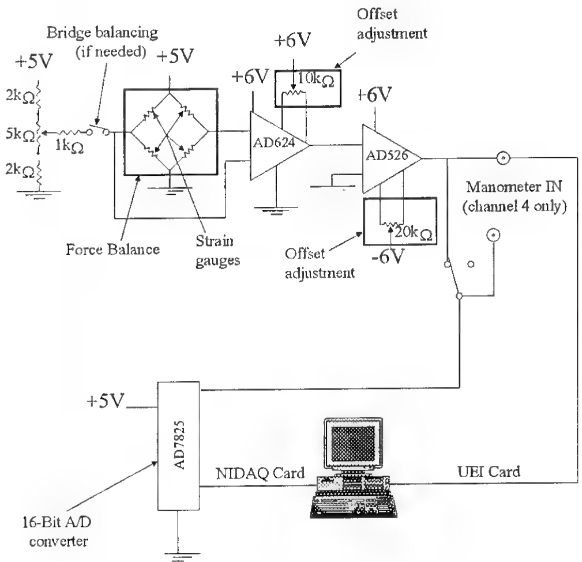


Figure 18: UND-FB2 balance electronics

Data acquisition

All the data was acquired using a PC-based data acquisition system running the LABVIEW® 5 graphical programming language. The NIDAQ card was first used for data acquisition. The UEI card is now used with the new balance when severe noise interferes with the data and the NIDAQ card cannot be used.

The data acquisition process with the new balance was automated. The angle of attack can be automatically varied from a pre-determined list of angles of attack. The range is usually adjusted in order to be able to observe stall.

Specifications

Since the force/moment balance includes very sensitive flexures and strain gauges, the applied forces and moment cannot exceed certain limits. These limiting forces and moment were determined conservatively and are listed in Table 2. The limiting forces and moment for the UND-FB1 balance are also included for comparison (see Huber, 1985). In order to be able to move the balance and mount the models without permanently deforming the flexures, locking pins are used to restrain the balance. These locking pins must be removed when taking data.

Sources of noise

For all measurements, digital filtering in LABVIEW® was necessary to reduce noise generated by the servomotor used to change the angle of

	UND-FB2	UND-FB1
Positive lift	$7.0\,N$	$39.2\,N$
Negative lift	$-3.5\,N$	$-14.7\,N$
Positive drag	$2.0\,N$	$14.7\,N$
Moment	$15.0\,N \cdot cm$	$226\,N \cdot cm$

Table 2: Maximum force/moment balance specifications

attack, and also the motor of the water tunnel when water tunnel tests were performed. A low-pass Butterworth filter with a cut-off frequency of 50 Hz and of order 5 was used. A study on the effect of the filter and its order showed that the mean voltages were basically not affected, but the standard deviations of the means were greatly reduced. It was discovered during preliminary calibrations with the NIDAQ card that the servomotor was causing noise in the data. With the motor ON, the standard deviations of the samples (4,000 data points measured at a sampling frequency of 500 Hz) were larger than those without the motor ON, although the mean values, thus the calibration coefficients, were the same. It was found that isolating the motor from the balance helped to reduce the standard deviations. A thin plastic sheet was then placed between the aluminum motor support and the aluminum top plate, lift platform, of the balance. Moreover, plastic screws were used to mount the motor support to the balance. This eliminated any aluminum/aluminum contact between the motor and the balance. Noise caused by a metal-to-metal contact between a force/moment balance and a motor was also detected in a previous investigation at the University of Notre Dame (Pelletier, 1998). Figure 19 shows the standard deviations of the samples for a lift channel calibration example with and without the isolation plastic.

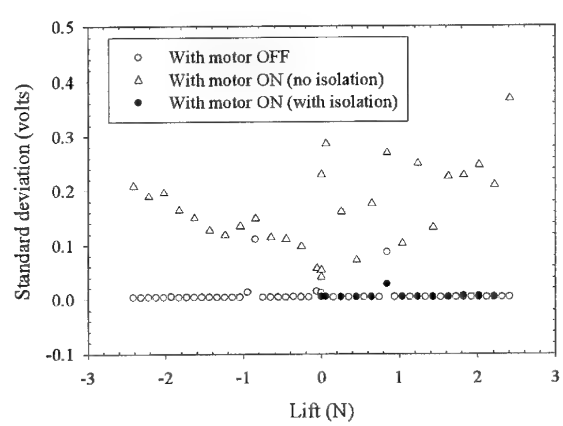


Figure 19: Effect of the motor on the standard deviation with NIDAQ data acquisition card

Calibration

After construction of the balance and electronics, calibrations were performed to ascertain the linearity of the balance for all its *independent* axes: lift, drag and moment. These calibrations were performed by moving the upper plate, lift platform, of the balance or by applying a torque to the moment sensor by placing precision weights of known mass in a container connected to the plate, or moment sensor. The container was connected to the upper plate by running a string over the calibration pulley aligned with the axis to calibrate (for lift and drag) or perpendicular to the torque applicator (pin connected to the sting used to apply a known torque) for the moment calibration. For this moment calibration, the lift and drag locking pins were used to prevent movement in the lift and drag direction as a moment was applied to the sensor. Several calibrations were performed to look for repeatability and linearity. Figures 20 through 22 show examples of the calibration curves that were repeatedly obtained.

UND-FB2 performance

Once the new balance and its electronics were built and calibrations had been performed, it was tested to see if the results compared to published data. All results presented in this paper have been corrected for solid blockage, wake blockage and streamlined curvature using techniques presented by Pankhurst and Holder (1952) and Rae and Pope (1984). A series of two-dimensional tests were conducted on different models.

Models

In the balance validation phase, two circular cylinders were tested. The diameters of the two cylinders were $0.75\,in$ ($1.9\,cm$) and $1.255\,in$ ($3.2\,cm$) and they both had a length of $12\,in$ ($30.5\,cm$). An Eppler 61 airfoil model, whose profile was shown in Figure 4, was also used to test the balance. The model also had a length of $12\,in$ ($30.5\,cm$) and a chord of $4.906\,in$ ($12.5\,cm$).

Cylinder results

The new balance was first tested by measuring the two-dimensional drag on two circular cylinders in the low-speed wind tunnel. Figure 23 shows the drag coefficient as a function of Reynolds number. Results of the present investigation were compared to results by Wieselsberger, digitized from *Boundary-Layer Theory* by Schlichting (1979). There is a good agreement between the two sets of data.

Eppler 61 airfoil results

The balance was then tested by measuring the two-dimensional lift and drag on the Eppler 61 airfoil. Results

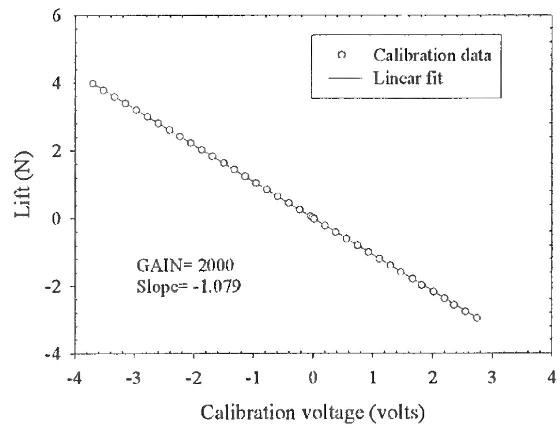


Figure 20: Lift calibration for the new balance

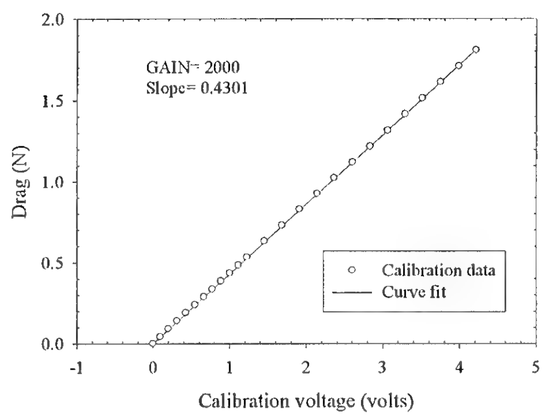


Figure 21: Drag calibration for the new balance

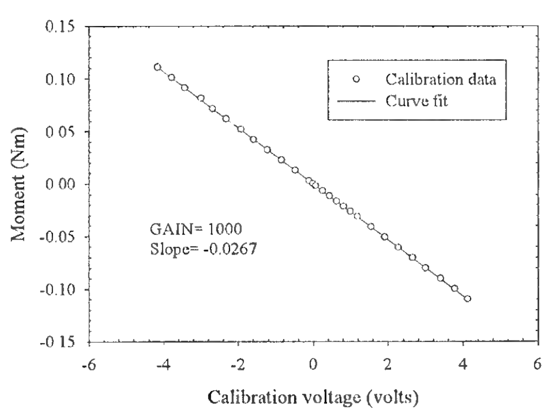


Figure 22: Pitching moment calibration for the new balance

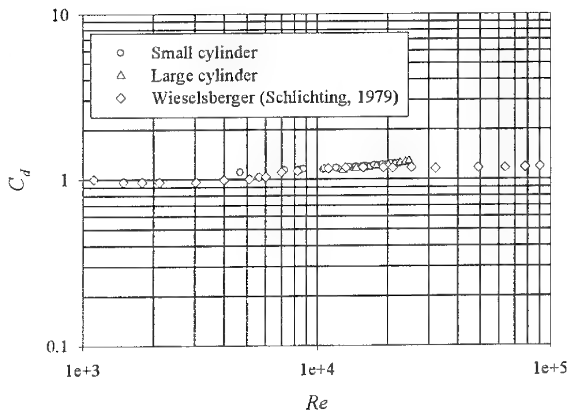


Figure 23: 2D drag coefficient of two circular cylinders with UND-FB2

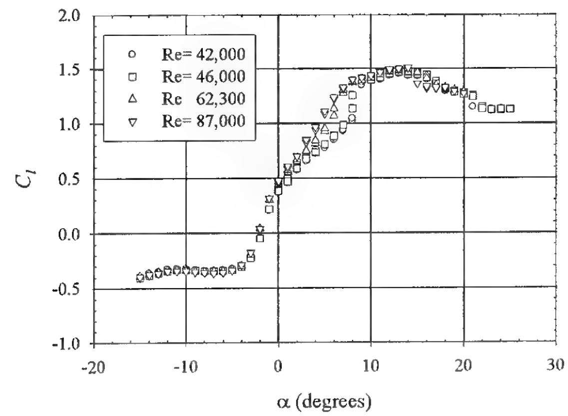


Figure 24: 2D lift coefficient on the Eppler 61 airfoil in the wind tunnel with UND-FB2

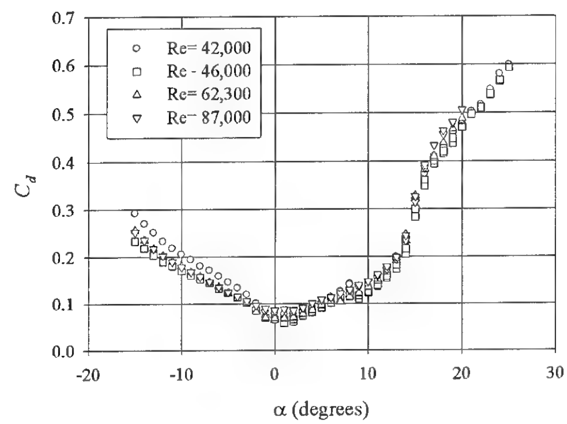


Figure 25: 2D drag coefficient on the Eppler 61 airfoil in the wind tunnel with UND-FB2

were obtained in the wind tunnel and the water tunnel for several Reynolds numbers. Figures 24 and 25 show the two-dimensional lift and drag coefficients respectively in the wind tunnel for different *nominal* Reynolds numbers, i.e., values used to adjust the velocity in the tunnel with the model at $\alpha = 0°$.

Results for C_l indicate a significant difference between results at $Re_c > 60,000$ and those for $Re_c < 60,000$. For large Re_c, C_l increases smoothly with angle of attack α. For smaller Re_c, the lift-curve slope C_{l_α} is smaller for $2° \leq \alpha \leq 8°$ and there is a sharp rise in C_l at $\alpha \approx 8°$. Similar results have been obtained by Althaus (1980) and shown in Figure 26. Althaus used a strain gauge balance arrangement to measure lift and a wake rake to measure drag. A drawback of using a wake rake will be addressed later. Althaus did observe a small hysteresis loop at low Reynolds numbers. No apparent hysteresis was observed in the current study.

The sharp rise in C_l at low Reynolds numbers is believed to be the result of a laminar separation bubble on the upper surface of the wing. O'Meara and Mueller (1987) showed that the length of the separation bubble tends to increase with a reduction in Re_c. A reduction in the turbulence intensity also tends to increase the length of the bubble. The lift-curve slope is affected by separation bubbles. A longer bubble is usually associated with a decrease in the lift-curve slope (Bastedo and Mueller, 1985). This is the kind of behavior observed with the Eppler 61 airfoil in this investigation. Flow visualization by Mueller and Burns (1982) showed the presence of a separation bubble on the Eppler 61 airfoil at $Rc_c = 46,000$.

In the water tunnel, the turbulence intensity is larger than in the wind tunnel. Therefore, the smaller C_{l_α} and sharp rise in C_l observed in the wind tunnel for $2° \leq \alpha \leq 8°$ might not be present at all in the water tunnel data for the same Reynolds numbers. This is exactly what happened for $Re_c = 42,000$ and $Re_c = 46,000$, as shown in Figure 27. The drag coefficient appears to be less affected, within the uncertainty of the measurements. Figure 28 shows the C_d curves obtained in the water tunnel for the Eppler 61 airfoil.

Figures 29 through 31 show comparisons of the current Eppler 61 results with published data. There is, in general, a good agreement between the current data and published data. The most significant difference is in the stall angle; there appears to be a 2° difference in α_{stall}.

Measurement uncertainty with UND-FB2

Uncertainties in the measurements were computed using the Kline-McClintock technique (Kline and McClintock, 1953) for error propagation. As indicated earlier, the two main sources of uncertainty were the quantization error and the uncertainty arising from the standard deviation of a given mean output voltage. The quantiza-

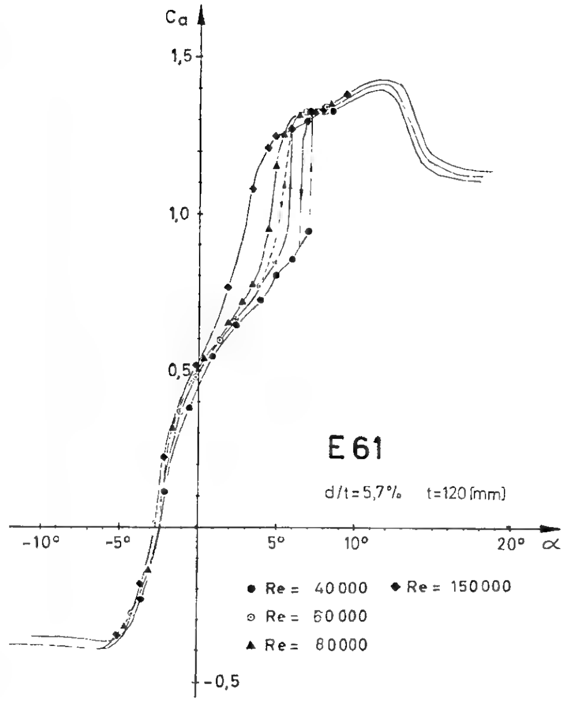


Figure 26: Althaus' results for 2D lift coefficient on the Eppler 61 airfoil (Althaus, 1980)

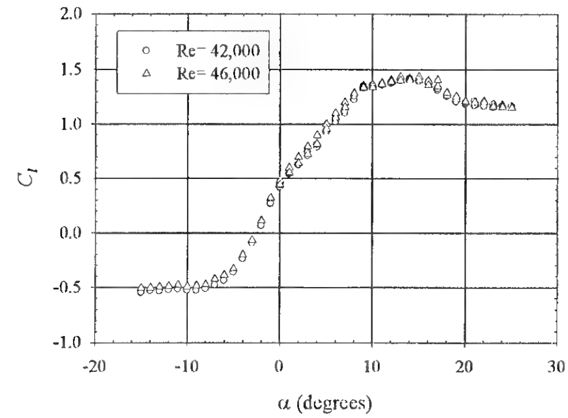


Figure 27: 2D lift coefficient on the Eppler 61 airfoil in the water tunnel with UND-FB2

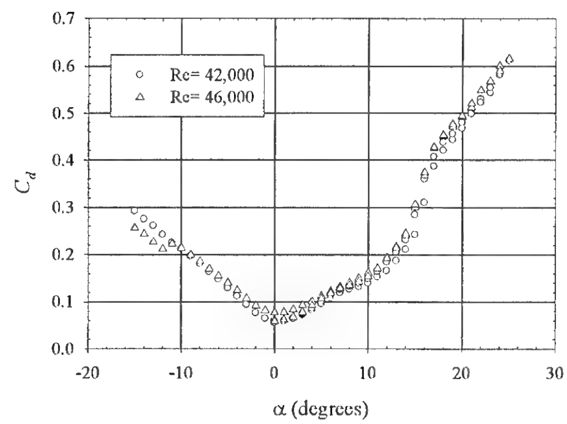


Figure 28: 2D drag coefficient on the Eppler 61 airfoil in the water tunnel with UND-FB2

tion error, described earlier, was smaller with the NIDAQ card than with the UEI card due to the better resolution of the A/D converter (16 bits compared to 12 bits). The uncertainty in the angle of attack was determined to be on the order of $0.2° - 0.3°$. The error from the encoder was negligible. The encoder offered an excellent resolution of 2,000 counts per degree, which gave an uncertainty of 5×10^{-4}. Figures 32 and 33 show a comparison of wind tunnel and water tunnel results for the Eppler 61 airfoil at $Re_c = 42,000$. Error bars indicate the uncertainty in C_l and C_d when the NIDAQ card is used. The average uncertainties for C_l and C_d in the range of angles of attack tested are approximately 4% in the water tunnel and 6% in the wind tunnel.

The new balance in itself is also more sensitive than the old balance. This allows experiments at smaller velocities in the water tunnel. As of now, results with different wings have shown a high degree of repeatability for Reynolds numbers as low as $40,000$. A major challenge in measurements at Reynolds numbers below $40,000$ is being able to measure drag accurately. At $Re_c = 20,000$, the minimum drag can be as low as $0.02\,N$, which corresponds to a load of approximately 2 grams. A fine drag calibration of the balance showed that 1 gram was sufficient to deflect the drag flexure and yield a reasonable output voltage. However, this deflection is often on the order of signal noise.

Results for thin wings

This section will present results for thin flat and cambered wings. Some additional issues associated with determining aerodynamic characteristics as a function of Reynolds numbers will also be addressed. Accurate measurements of C_l and C_d with endplates and small aspect-ratio models are difficult to obtain at low Reynolds numbers because of the interaction between the thick boundary layers on the endplates and the flow around the wing, which results into a three-dimensional flow along the span of the model. This must be kept in mind when examining the following results.

Flat-plate wings

Some results for the flat-plate models (two endplates for 2D tests and one endplate for semi aspect-ratio tests)

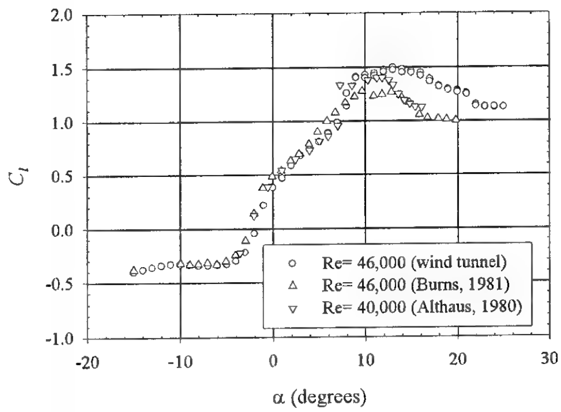


Figure 29: Comparison of 2D lift coefficient on the Eppler 61 airfoil and published data with UND-FB2

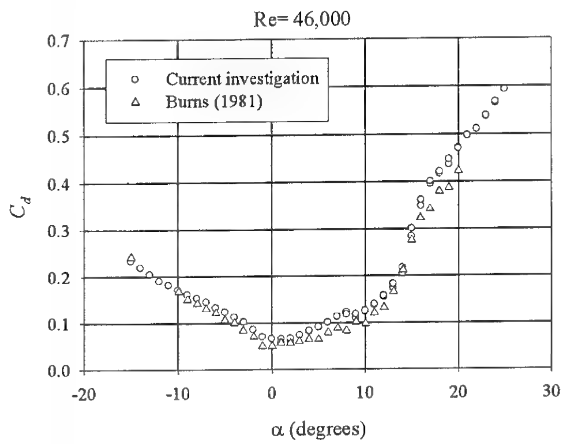


Figure 30: Comparison of 2D drag coefficient on the Eppler 61 airfoil and published data with UND-FB2

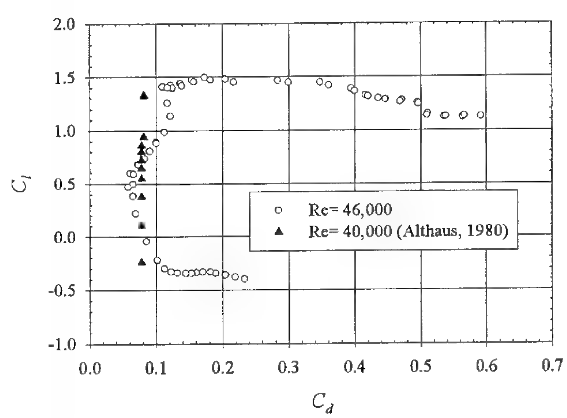


Figure 31: Comparison of 2D drag polar for the Eppler 61 airfoil and published data with UND-FB2

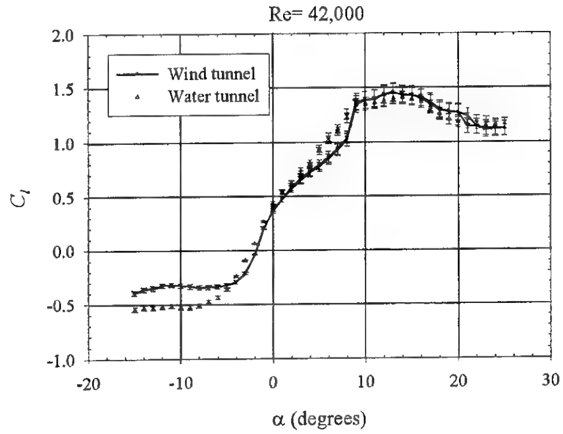


Figure 32: Comparison of the 2D lift coefficient on the Eppler 61 airfoil in wind and water tunnels with UND-FB2

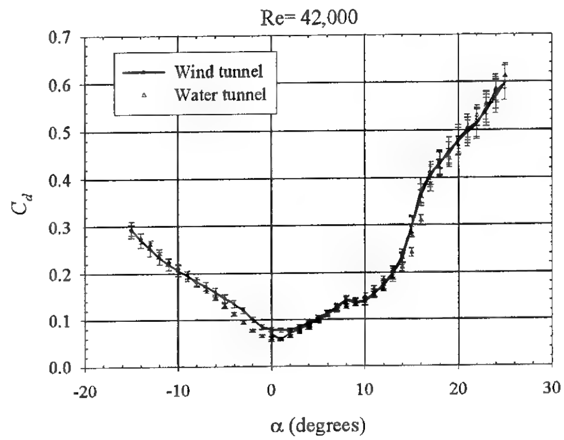


Figure 33: Comparison of the 2D drag coefficient on the Eppler 61 airfoil in wind and water tunnels with UND-FB2

can be seen in Figures 34 through 39 for $Re_c = 80,000$ and $Re_c = 140,000$. Figures 34 and 37 show a significant reduction in the lift-curve slope C_{L_α} for semi-infinite wings.

The lift-curve slope values obtained from the wind tunnel data are compared to theoretical values for thin wings of different semi-span aspect ratios in Figure 40. Equation 1 from Anderson (1991) was used to estimate the theoretical values of C_{L_α}:

$$C_{L_\alpha} = a = \frac{a_0}{1 + \left(\frac{a_0 * 57.3}{\pi \mathrm{AR}}\right)(1+\tau)}, \qquad (1)$$

where a_0 is the 2D lift-curve slope in 1/degrees, AR is the aspect ratio of the full wing ($\mathrm{AR} = 2 * \mathrm{sAR}$) and τ is the Glauert parameter (equivalent to an induced drag factor) varying typically between 0.05 and 0.25. The 2D value a_0 was determined to be $a_0 = 0.0938/\mathrm{deg}$. This corresponds to the average of all the slopes C_{L_α} (for all

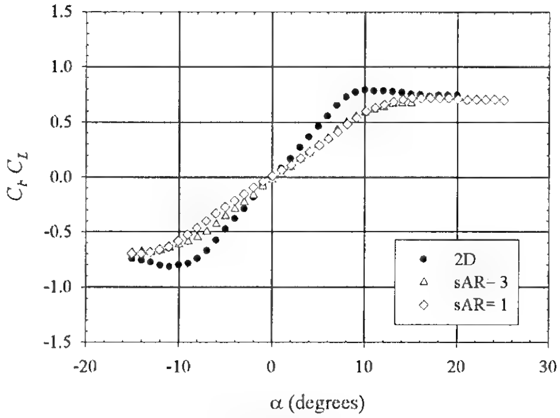


Figure 34: Lift coefficient on flat plates at $Re_c = 80,000$ *with UND-FB1*

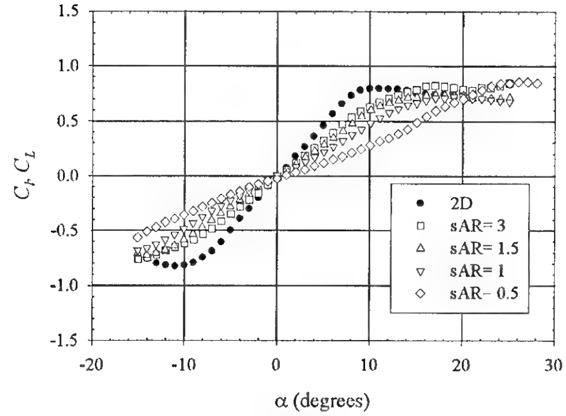


Figure 37: Lift coefficient on flat plates at $Re_c = 140,000$ *with UND-FB1*

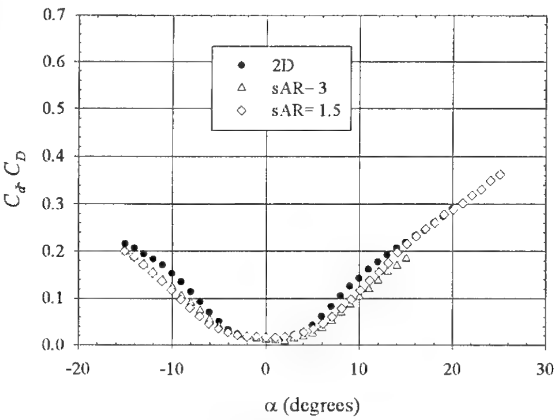


Figure 35: Drag coefficient on flat plates at $Re_c = 80,000$ *with UND-FB1*

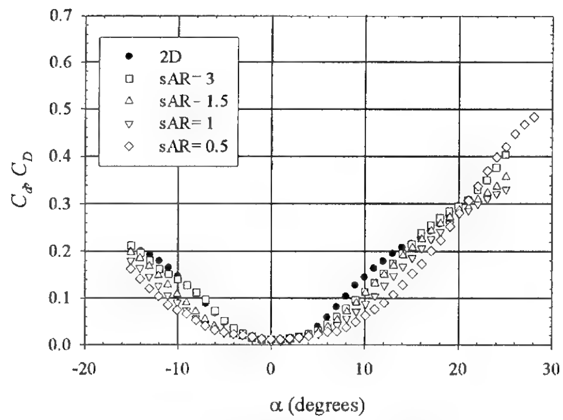


Figure 38: Drag coefficient on flat plates at $Re_c = 140,000$ *with UND-FB1*

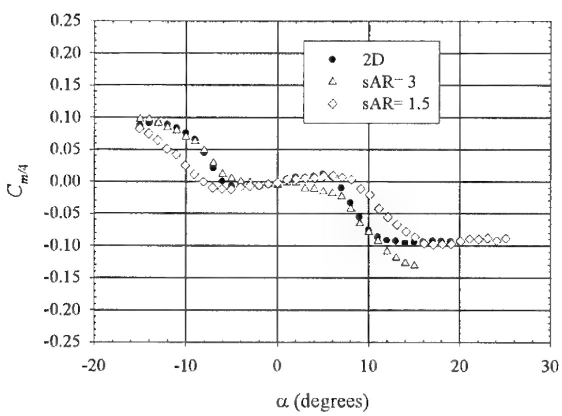


Figure 36: Pitching moment coefficient on flat plates at $Re_c = 80,000$ *with UND-FB1*

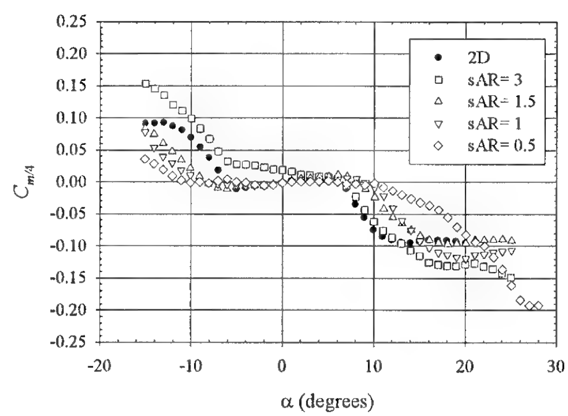


Figure 39: Pitching moment coefficient on flat plates at $Re_c = 140,000$ *with UND-FB1*

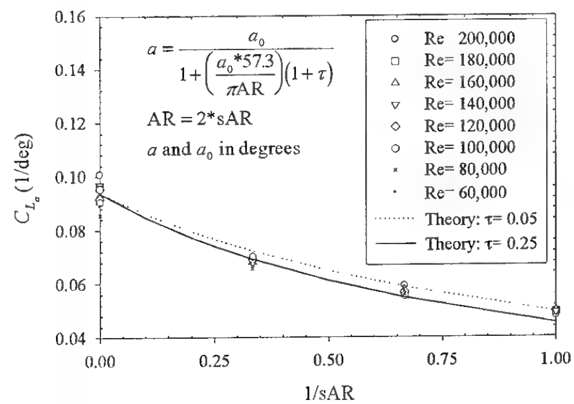


Figure 40: Lift-curve slope for flat-plate models in wind tunnel with UND-FB1

Reynolds numbers considered) for an infinite aspect ratio ($1/\mathrm{sAR} = 0$). This value was picked instead of the conventional value of $a_0 = 2\pi/\mathrm{rad} = 0.1/\mathrm{deg}$ given by thin-airfoil theory. Figure 40 shows a very good agreement between the experimental values of C_{L_α} and the theoretical values estimated by Equation 1.

As the aspect ratio was decreased, Figures 34 and 37 also show that the linear region of the C_L vs α curve became longer and α_{stall} tended to increase. Moreover, both figures show that there was no abrupt stall for low aspect-ratio wings. For these low aspect ratios, C_L often reached a plateau and then remained relatively constant, or even started to increase, for increasing angles of attack.

Changing the aspect ratio of the models did not appear to have a measurable effect on the drag coefficient at $Re_c = 80,000$, as shown in Figure 35. At $Re_c = 140,000$, increasing the aspect ratio had the unexpected effect of increasing C_D for angles greater than $5°$. No measurable difference was encountered in the range $-5° \leq \alpha \leq 5°$.

Finally, Figures 36 and 39 show the pitching moment at the quarter chord. Both figures indicate a slightly positive slope C_{m_α} around $\alpha = 0°$, even when considering the uncertainty. This would imply that the flat-plate models were statically unstable around $\alpha = 0°$. Increasing the Reynolds number from 80,000 to 140,000 tended to reduce the slope of $C_{m/4}$. The model with a semi-span aspect ratio of 3 indicated an irregular behavior at $Re_c = 140,000$ for $C_{m/4}$; the pitching moment was not zero at $\alpha = 0°$. This case will have to be repeated.

Aerodynamic characteristics as a function of Reynolds number: a different method

For tests without endplates, another balance arrangement, denoted arrangement number 3, was used and is presented in Figure 41. The lift and drag forces measured by the balance were for the wing-sting combination. The lift on the sting was basically zero. However, the drag of the sting alone, which dominated the total wing-sting drag, was not zero and was subtracted from the wing-sting values to get the C_D of the flat-plate wing alone.

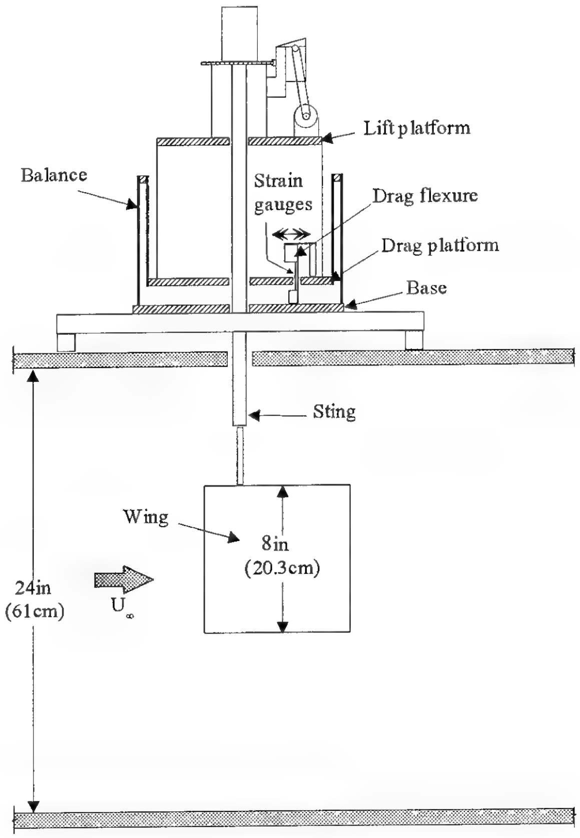


Figure 41: Balance arrangement (3) for finite wing tests with the new balance

In general, when investigators try to determine how $C_{L_{\max}}$ and $C_{D_{\min}}$ vary with Reynolds numbers, they determine $C_{L_{\max}}$ and $C_{D_{\min}}$ from C_L vs α and C_D vs α curves at different Reynolds numbers. It has been observed in this investigation that the values obtained do not always match the expected trend for drag because of the difficulty involved in measuring the very small drag forces. A slight offset in one C_L vs α or C_D vs α curve can lead to jagged $C_{L_{\max}}$ vs Re_c or $C_{D_{\min}}$ vs Re_c curves. A better technique was found to obtain $C_{D_{\min}}$ vs Re_c (the values of $C_{L_{\max}}$ vs Re_c are of lesser importance because micro-air vehicles will rarely fly at $C_{L_{\max}}$). For this technique, the angle of attack was fixed to the angle yielding the lowest C_D in a C_D vs α curve, and measurements were taken for a series of increasing and decreasing Reynolds numbers without stopping the tunnel. Results obtained with the new balance UND-FB2 using this technique on a finite wing of aspect ratio $\mathrm{AR} = 1$ in the wind tunnel, presented in Figures 42 and 43, are promising and the trends obtained matched the expected reduction in $C_{D_{\min}}$ with increasing Reynolds numbers.

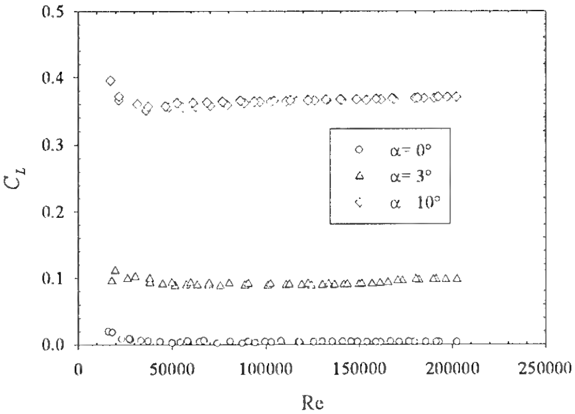
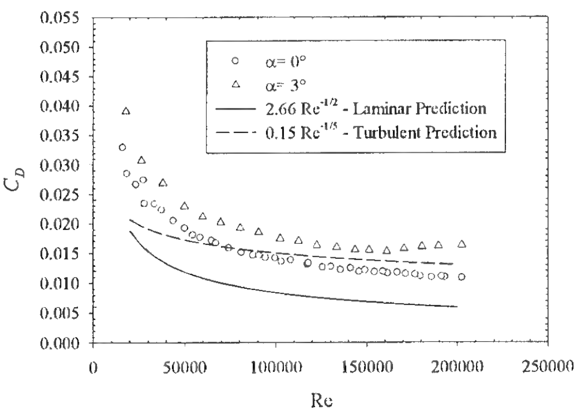
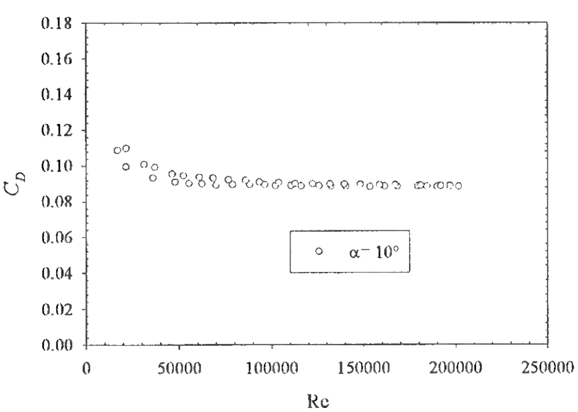


Figure 42: Lift coefficient variation with Re for AR $= 1$ *flat-plate wing with UND-FB2 (C8S8)*



(a) $\alpha = 0°$ and $3°$



(b) $\alpha = 10°$

Figure 43: Drag coefficient variation with Re for AR $= 1$ *flat-plate wing with UND-FB2 (C8S8)*

Results at the angle of attack for $\left(\frac{L}{D}\right)_{\max}(\alpha \approx 3°)$ also show an increase in C_L and a decrease in C_D with increasing Reynolds number. The results of Figure 42 at $\alpha = 10°$ are smaller than the lift coefficient presented in Figure 34 for a model with sAR $= 1$ because of the lack of an endplate. For a given model, adding an endplate leads to an increase in lift compared to the case without an endplate, as shown in Figure 44. Adding one endplate did not have a significant effect on C_D, as shown in Figure 45. The wing used for this series of tests had a nominal chord $c = 8\,in$ and span $b = 12\,in$ [C8S12].

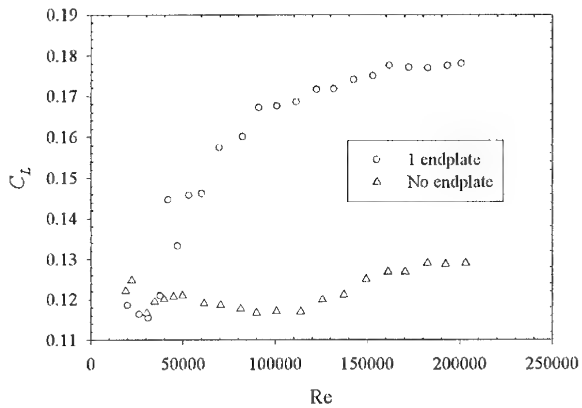


Figure 44: Lift coefficient variation with Re (C8S12) with UND-FB2 at $\alpha = 3°$

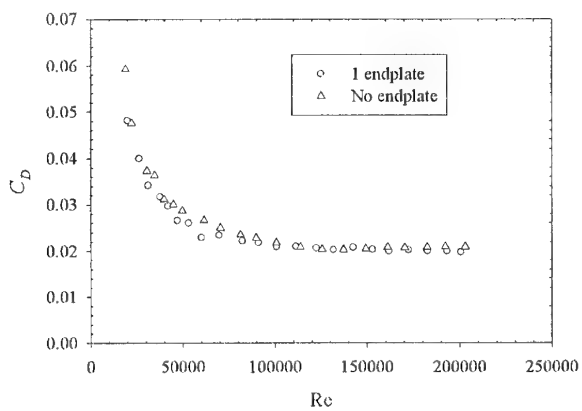


Figure 45: Drag coefficient variation with Re (C8S12) with UND-FB2 at $\alpha = 3°$

At an angle of attack $\alpha = 0°$, adding one or two endplates did not affect C_L for $Re_c > 60,000$; it remained basically around the expected value of zero, as shown in Figure 46. Moreover, adding endplates did not, once again, have a measurable effect on C_D, as presented in Figure 47. Since Figure 47 is for $\alpha = 0°$, it represents $C_{D_{\min}}$ versus Reynolds number for flat-plate wings. Experimental results are also compared to theory (Blasius: $C_{D_{\min}} = 2.66 Re^{-\frac{1}{2}}$) and CFD results in Figure 47. The

CFD results were computed by Greg Brooks (*Air Force Research Laboratory*, Wright-Patterson Air Force Base) using COBALT, a parallel, implicit, unstructured, finite volume laminar CFD code based on Godunov's exact Riemann method, developed by the *Air Force Research Laboratory* (see Strang, Tomaro and Grismer, 1999). All sets of data indicate the same trend. The experimental data was always larger than theory and the CFD results. This could have been caused by surface roughness, imperfect flow conditions, and so forth. Since all wind tunnel tests with the flat and cambered wings are usually conducted at Reynolds numbers greater than 60,000, the results presented in Figures 42 through 47 for $Re < 60,000$ should be analyzed with caution. The velocity in the wind tunnel is usually too low for $Re < 60,000$ to yield reliable results.

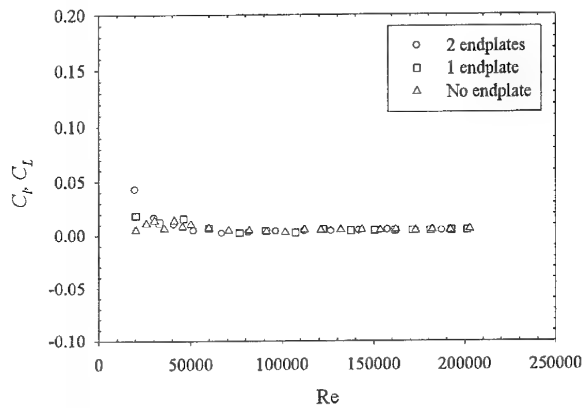


Figure 46: Lift coefficient variation with Re (C8S12) with UND-FB2 at $\alpha = 0°$

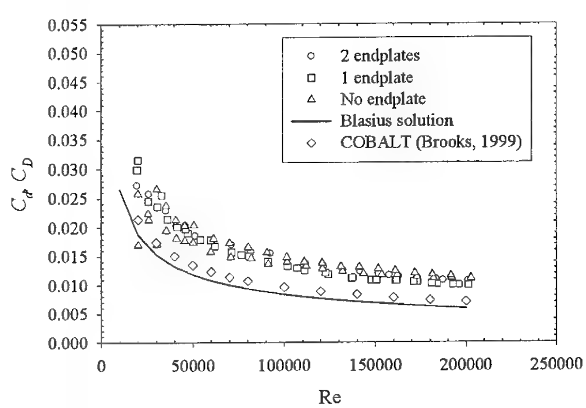


Figure 47: Drag coefficient variation with Re (C8S12) with UND-FB2 at $\alpha = 0°$

The results of Figure 47 seem to indicate that for thin flat-plate wings at $\alpha = 0°$ the drag coefficient acting on the wing is independent of aspect ratio. Results of Figure 47 were then compared to the drag coefficients

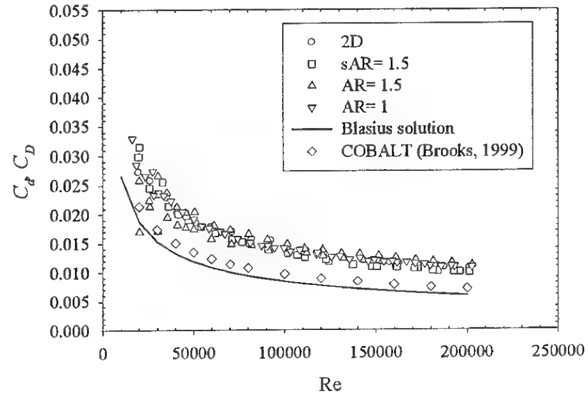


Figure 48: Minimum drag coefficient with Re for AR ≥ 1 flat-plate wings with UND-FB2

for the AR $= 1$ plate and no difference was obtained, as shown in Figure 48. For aspect ratios greater than one, the minimum drag coefficient is then independent of model size and the presence of endplates. For lower aspect ratios, preliminary tests indicated a larger $C_{D_{\min}}$. More work is in progress to fully understand the behavior of $C_{D_{\min}}$ as a function of Reynolds numbers for the very low aspect-ratio wings (AR < 1). Similar tests will also have to be conducted on the cambered wings. The non-measurable difference in $C_{D_{\min}}$ with Reynolds numbers might just be valid for flat-plate wings. Adding camber might change the results. Preliminary results seem to indicate this trend.

Cambered-plate wings

Results were also obtained for cambered-plate models using the balance arrangement with one or two endplates (semi-infinite or 2D tests). In general, camber led to better aerodynamic characteristics due to an increase in lift, even though drag also increased. Figures 49 through 54 show some results for the cambered plates at $Re_c = 60,000$ and $Re_c = 140,000$. With cambered plates, $C_{D_{\min}}$ was slightly larger than for flat plates. The maximum lift coefficient was also larger, as expected. Moreover, the variation in C_L with angle of attack at small angles was less linear for cambered plates than for flat plates. Finally, the behavior of the moment coefficient $C_{m/4}$ for the cambered plates was very different than the behavior with the flat plates. A rise in $C_{m/4}$ occurred after $\alpha \approx 5°$, leading to a hump at around $\alpha \approx 10°$. This was not observed with the flat plates. Flow visualization will hopefully explain this behavior.

Equation 1 was also used to compare the experimental values of C_{L_α} at $\alpha_{C_L=0}$ for the cambered plates to theoretical values. The 2D value a_0 used was $a_0 = 0.1097/\text{deg}$. Figure 55 shows a good agreement between theory and experiments.

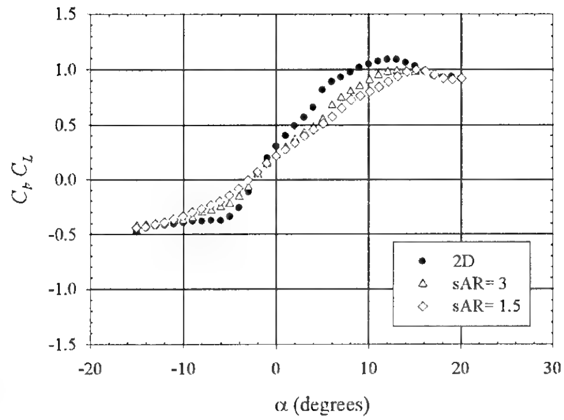


Figure 49: Lift coefficient on cambered plates at $Re_c = 60,000$ with UND-FB1

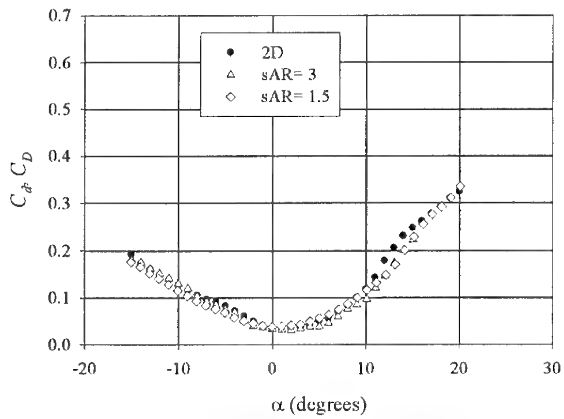


Figure 50: Drag coefficient on cambered plates at $Re_c = 60,000$ with UND-FB1

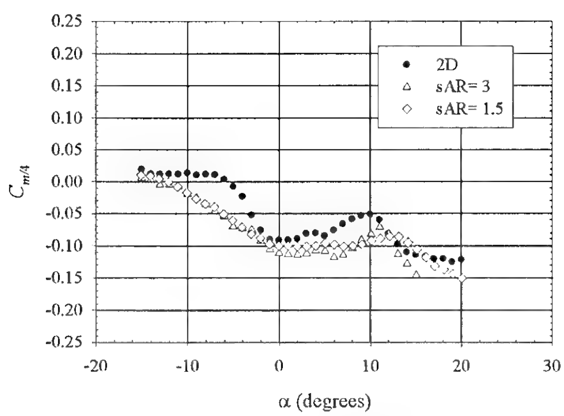


Figure 51: Pitching moment coefficient on cambered plates at $Re_c = 60,000$ with UND-FB1

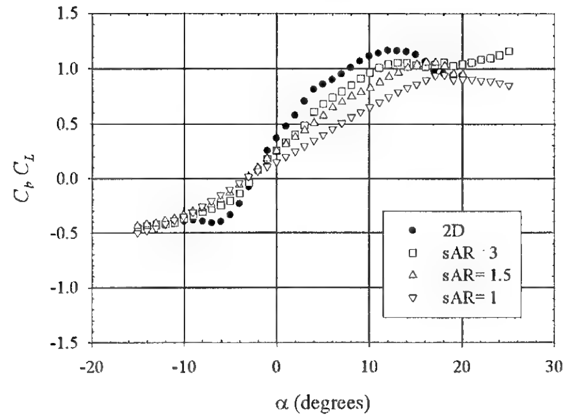


Figure 52: Lift coefficient on cambered plates at $Re_c = 140,000$ with UND-FB1

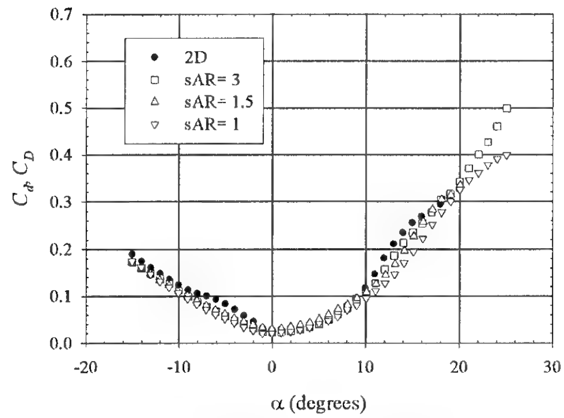


Figure 53: Drag coefficient on cambered plates at $Re_c = 140,000$ with UND-FB1

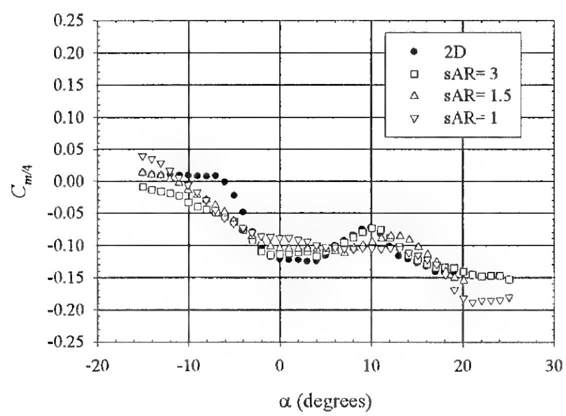


Figure 54: Pitching moment coefficient on cambered plates at $Re_c = 140,000$ with UND-FB1

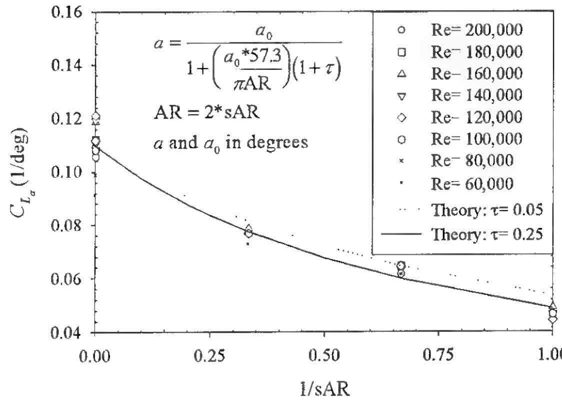


Figure 55: Lift-curve slope for cambered-plate models in wind tunnel with UND-FB1

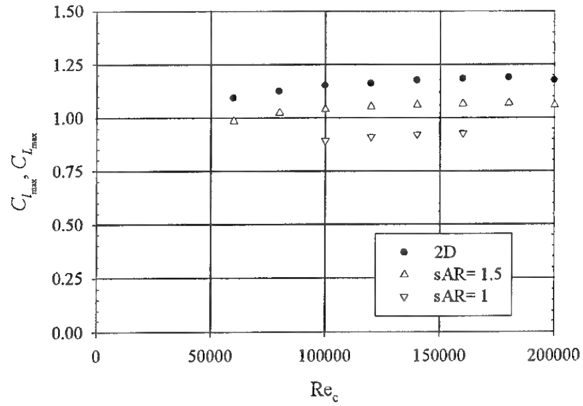


Figure 56: Maximum lift coefficient as a function of Re_c for cambered wings with UND-FB1

Since the cambered wings showed better aerodynamic characteristics, and hence are more suitable in the design of micro-air vehicles, only performance data for the cambered plates is presented. Figures 56 through 59 show the behavior of $C_{L_{\max}}$, $C_{D_{\min}}$, $\left(\frac{L}{D}\right)_{\max}$ and $\left(\frac{C_L^{3/2}}{C_D}\right)_{\max}$ as a function of Reynolds number. The maximum L/D ratio is related to the maximum range for a propeller driven airplane, while the maximum $C_L^{3/2}/C_D$ is related to best endurance (longest flying time possible). As expected, $C_{L_{\max}}$ increased with Reynolds number and aspect ratio in the range of Reynolds numbers tested. The same expected behavior was obtained for $\left(\frac{L}{D}\right)_{\max}$ and $\left(\frac{C_L^{3/2}}{C_D}\right)_{\max}$. On the other hand, $C_{D_{\min}}$ showed an increase with decreasing Reynolds number, as was also expected. The maximum L/D generally occurred at $\alpha = 3°$ to $4°$, while $\left(\frac{C_L^{3/2}}{C_D}\right)_{\max}$ occurred at $\alpha = 4°$ to $5°$. It is important to remember that the endplates have been shown to have an effect on the lift coefficients of flat-plate wings, and probably cambered-plate wings also. As mentioned earlier, the effect of the endplates on the drag characteristics of cambered-plate wings is still under investigation. The results presented in this report must then be analyzed with the possible effect of the endplates in mind; the numerical values should not be taken as the ultimate results. The effect of the endplates on the pitching moment has not been investigated for both flat-plate and cambered-plate wings.

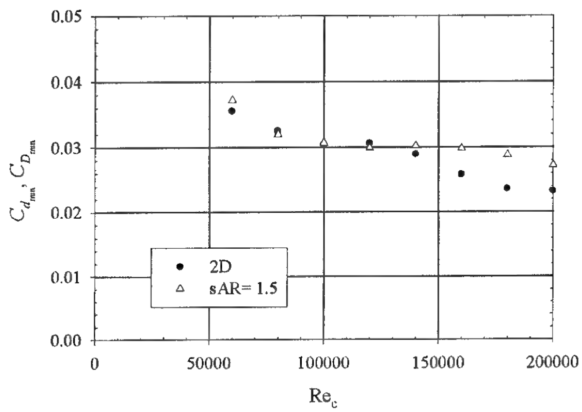


Figure 57: Minimum drag coefficient as a function of Re_c for cambered wings with UND-FB1

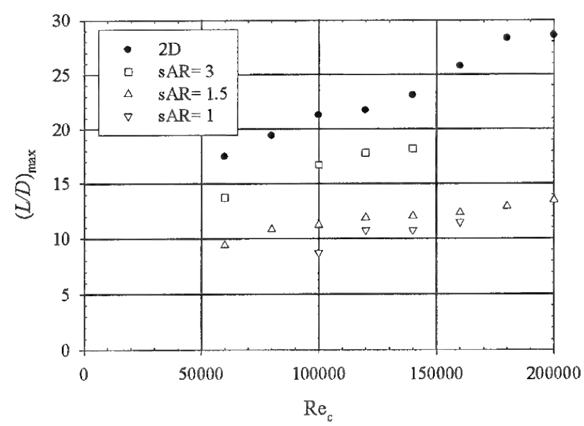


Figure 58: Maximum L/D ratio as a function of Re_c for cambered wings with UND-FB1

Effect of trailing-edge geometry

Four models [$c = 8\,in$ ($c = 20.3\,cm$) and $b = 12\,in$ ($b = 30.5\,cm$)] were tested in the wind tunnel at several chord Reynolds numbers to see if the trailing-edge geometry had any influence on the aerodynamic characteristics of flat plates and cambered plates at low chord

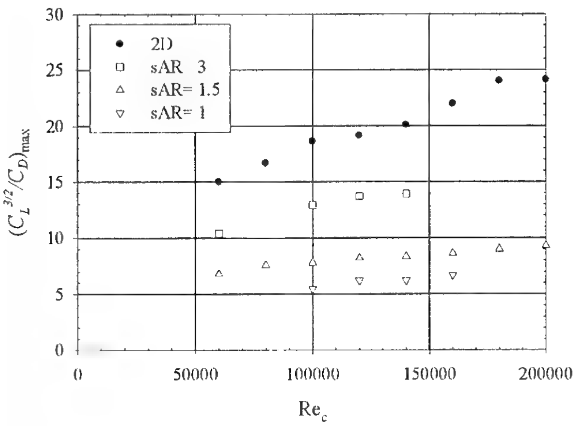


Figure 59: Maximum $C_L^{3/2}/C_D$ ratio as a function of Re_c for cambered wings with UND-FB1

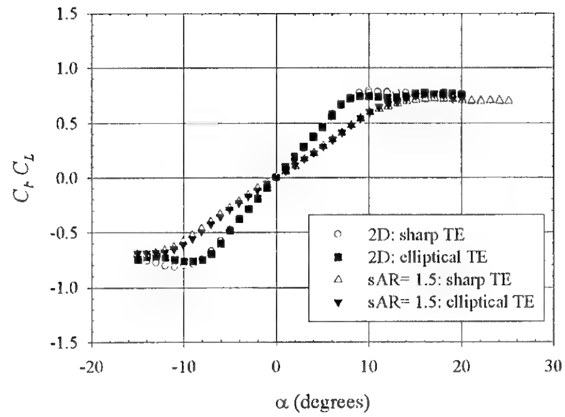


Figure 60: Trailing-edge geometry effect on lift coefficient at $Re_c = 80,000$ on flat plates in the wind tunnel with UND-FB1

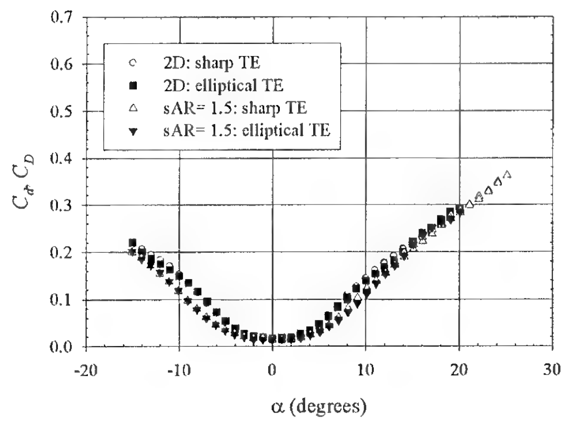


Figure 61: Trailing-edge geometry effect on drag coefficient at $Re_c = 80,000$ on flat plates in the wind tunnel with UND-FB1

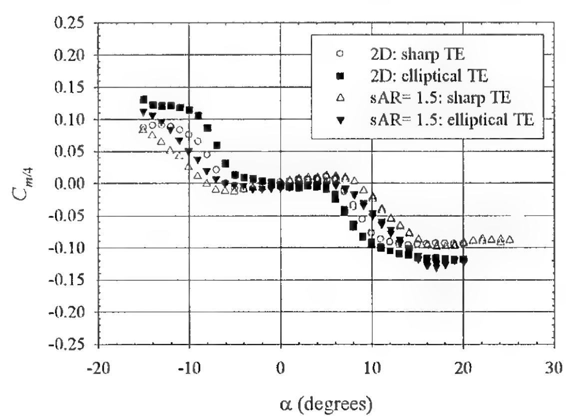


Figure 62: Trailing-edge geometry effect on pitching moment coefficient at $Re_c = 80,000$ on flat plates in the wind tunnel with UND-FB1

Reynolds numbers. The first two models had a tapered trailing edge, while the other two models had an elliptical trailing edge. Results were obtained for infinite models (2D case) and models with a semi-span aspect ratio sAR $= 1.5$. For both cases, no significant difference was observed in C_L or C_l, and C_D or C_d, as a function of trailing-edge geometry, as shown in Figures 60 and 61 for $Re_c = 80,000$. A difference was however observed in the moment coefficient $C_{m/4}$. For a sharp trailing edge, C_{m_α} often appeared to be positive around $\alpha = 0°$, even with the uncertainty considered (error bars in $C_{m/4}$ are about the size of the symbols). With the elliptical trailing edge, the 2D cases at $Re_c = 80,000$ showed a stable negative value of C_{m_α}, as shown in Figure 62. For a semi-span aspect ratio of 1.5, C_{m_α} was basically zero at $\alpha = 0°$. Flow visualization to be performed later may explain this phenomenon.

With the cambered plates, there was basically no difference between a sharp trailing edge and an elliptical trailing edge at $Re_c = 80,000$, as shown in Figures 63 through 65. Results with the cambered plates seem to agree with Laitone (Laitone, 1996 and 1997), who showed that at low Reynolds numbers, a sharp trailing edge is not as critical as for larger Reynolds numbers.

The influence of the leading-edge geometry was also investigated by looking at the lift and drag characteristics of a flat-plate model in 2D and sAR $= 1.5$ configurations in the water tunnel at $Re_c = 39,000$ and $Re_c = 60,000$. For these tests, the existing C8S12 model was rotated 180 degrees (tapered leading edge and elliptical trailing edge). No difference was noticed in the results for lift and drag. Laitone (1996 and 1997) did notice a significant increase in lift at $Re_c = 20,700$ for a *thicker* reversed NACA 0012 airfoil (the sharp trailing edge was facing the flow). Further tests will be conducted in the wind tunnel at larger Reynolds numbers on flat-plate and cambered-plate wings to complete this study of the leading-edge geometry effect

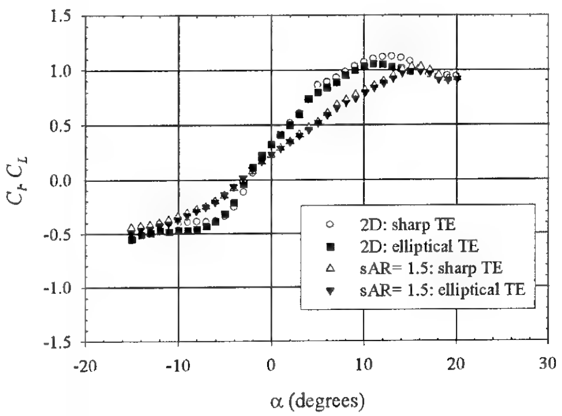


Figure 63: Trailing-edge geometry effect on lift coefficient at $Re_c = 80,000$ on cambered plates in the wind tunnel with UND-FB1

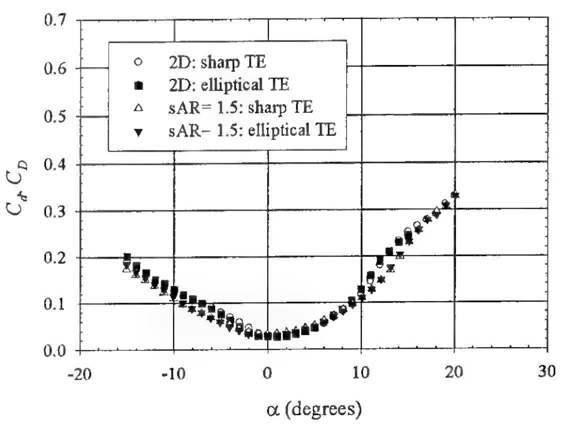


Figure 64: Trailing-edge geometry effect on drag coefficient at $Re_c = 80,000$ on cambered plates in the wind tunnel with UND-FB1

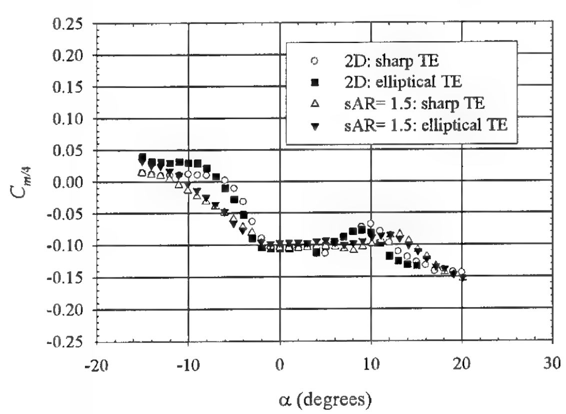


Figure 65: Trailing-edge geometry effect on pitching moment coefficient at $Re_c = 80,000$ on cambered plates in the wind tunnel with UND-FB1

on the aerodynamic characteristics of thin wings/airfoils.

Effect of freestream turbulence

Mueller et al. (1983) showed that an increase in freestream turbulence intensity reduced the minimum drag acting on an 11% thick Lissaman 7769 airfoil at $Re_c = 150,000$ and slightly increased $C_{l_{\max}}$. This was caused by an earlier laminar shear layer transition, hence earlier flow reattachment (i.e., a shorter separation bubble), with a larger turbulence intensity. At large angles of attack where the flow is mostly separated, they observed an increase in drag coefficient with an increase in turbulence intensity. Increasing the turbulence intensity also helped to eliminate some of the hysteresis encountered in C_l and C_d for that particular airfoil.

Pohlen (1983) also looked at the influence of turbulence intensity on a 13% thick Miley airfoil (M06-13-128) (see Miley, 1972). He found that increasing the turbulence intensity helped to reduce the hysteresis in C_l and C_d and slightly improved airfoil performance.

Tests were then conducted in the wind tunnel with different screens upstream of the flat-plate sAR = 1.5 models and a flow restrictor downstream of the model to see if a difference in the turbulence intensity could result in different aerodynamic properties for the models used in this investigation. The flow restrictor, or strawbox, was made of drinking straws packed in a wooden frame and placed between the test section and the diffuser. The additional turbulence intensity generated by the strawbox was determined to be approximately 0.05% (Brendel and Huber, 1984). Table 3 indicates the mesh size and nominal freestream turbulence intensity in the test section with only a screen present (no flow restrictor).

Screen	Mesh size (meshes/cm)	Wire diameter (mm)	Turbulence %
Fine	7.09	0.245	0.25
Medium	3.15	0.508	0.45
Coarse	0.64	1.397	1.3

Table 3: Turbulence screen data (Pohlen, 1983; and Brendel and Huber, 1984)

No measurable differences were observed in the results for different turbulence intensities at $Re_c = 60,000$ on the sAR = 1.5 flat-plate model, as shown in Figures 66 and 67. Only a slight increase in $C_{L_{\max}}$ and an increase in C_D for large angles of attack was noticed for the case with the fine mesh and with the strawbox. All other cases gave the same results. Therefore, the effect of turbulence intensity appeared to be minimal in the wind tunnel for the models tested. Similar results were

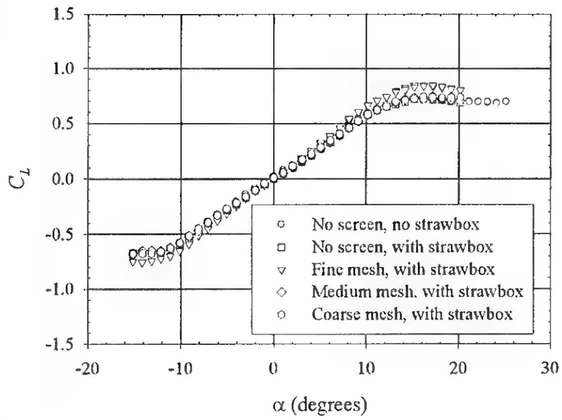


Figure 66: Freestream turbulence effect on lift coefficient at $Re_c = 60,000$ *in the wind tunnel for the* sAR $= 1.5$ *flat-plate model with UND-FB1*

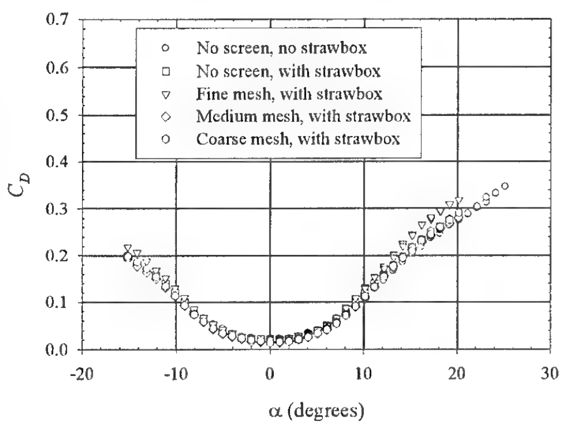


Figure 67: Freestream turbulence effect on drag coefficient at $Re_c = 60,000$ *in the wind tunnel for the* sAR $= 1.5$ *flat-plate model with UND-FB1*

obtained at $Re_c = 120,000$ in the wind tunnel, and at $Re_c = 39,000$ and $Re_c = 60,000$ in the water tunnel.

Effect of endplates on 2D measurements

It has been shown in previous experiments at Notre Dame that the presence of the endplates during 2D tests usually leads to a larger $C_{D_{min}}$. For an 18% thick airfoil (NACA $66_3 - 018$), Mueller and Jansen (1982) showed that the interaction between the endplates and the model resulted in a 20% increase in $C_{d_{min}}$ at Reynolds numbers between $60,000$ and $200,000$.

Since most of the tests in the current investigation were conducted at very low speeds, the interaction between the boundary layer growing on the endplates and the wing created a *corner* flow, as depicted in Figure 68, which acted over a significant portion of the wing span and significantly altered the 2-dimensionality of the flow over the wing. This phenomenon of the corner flow has been investigated by several authors, including Hawthorne (1954) and Barber (1978) who looked at the flow around struts near a wall.

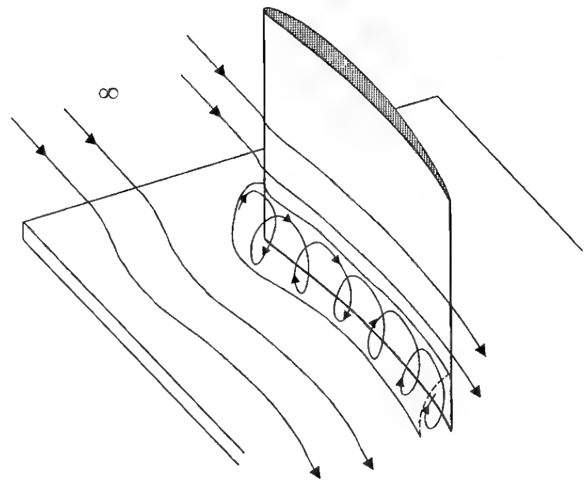


Figure 68: Schematic of corner flow on wing

In order to verify the effect of the endplates on the aerodynamic characteristics of the Eppler 61 airfoil, a 3-piece Eppler 61 model was used. With this setup, a section of an Eppler 61 model was free to move between two other sections of the same airfoil. These two other sections were fixed to the endplates in the wind tunnel, as shown in Figure 69, at the same angle of attack as the middle section. A small gap was present between the end models and the center piece connected to the force balance. Figure 70 shows the three pieces of the 3-piece Eppler 61 model.

The angle of attack of the 3-piece Eppler 61 model was adjusted to a certain value and the velocity in the tunnel, hence the Reynolds number, was varied. The behavior of C_d and C_l was measured. From the previous 2D results on the Eppler 61 airfoil, it was determined that $C_{d_{min}}$ occurred at $\alpha = 0°$ and the angle for zero lift was about $\alpha = -2°$. The behavior of C_d vs Re_c was first obtained at these two angles of attack. Figures 71 and 72 show that the drag coefficient with the 3-piece Eppler 61 model was much smaller than with the full model. This result is similar to that reported by Mueller and Jansen (1982) for the NACA $66_3 - 018$ airfoil. The lift coefficient with the 3-piece model was higher than with the full model. The aerodynamic characteristics with the 3-piece model were closer to true 2-dimensional results, where a larger C_l and smaller C_d would normally be expected. The behavior of C_l and C_d with Reynolds numbers also followed the expected trends. A reduction in C_d and an increase in C_l were observed with increasing Reynolds numbers. Results from Althaus (1980) and de Vries et al. (1980) are also included in the figures for comparison. As was mentioned earlier for Althaus,

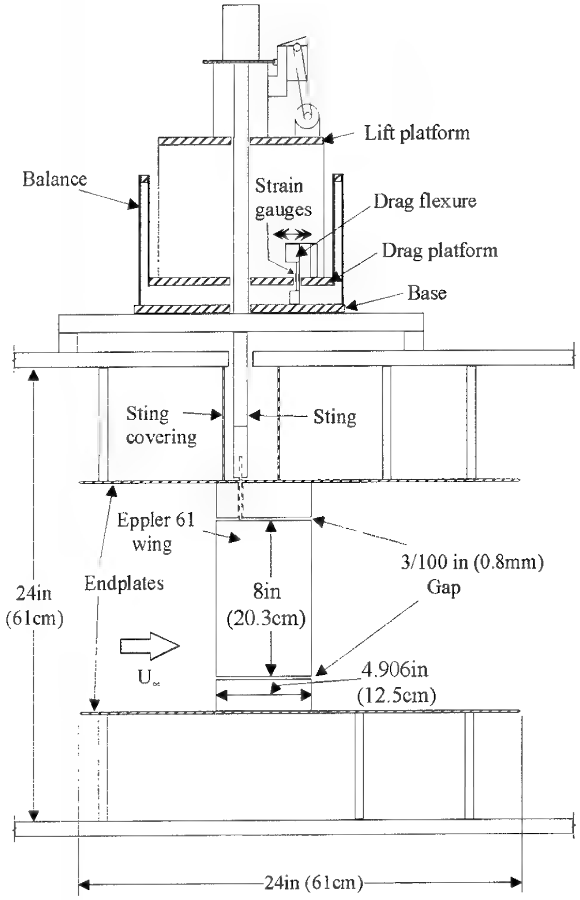
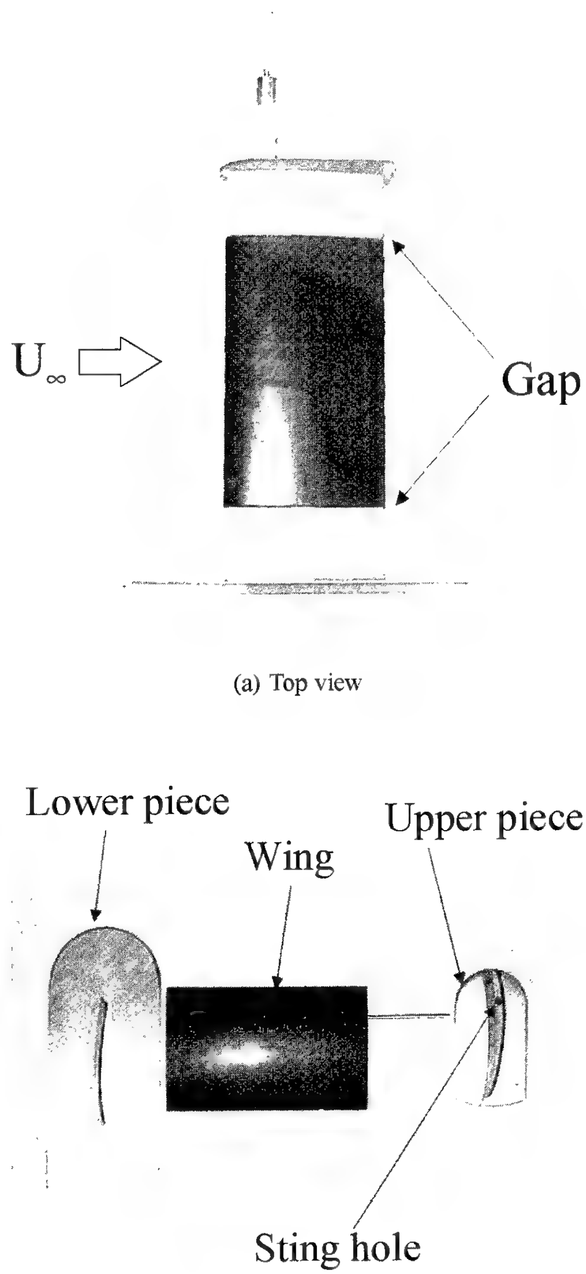


Figure 69: New-balance arrangement for 3-piece Eppler 61 airfoil tests in wind tunnel



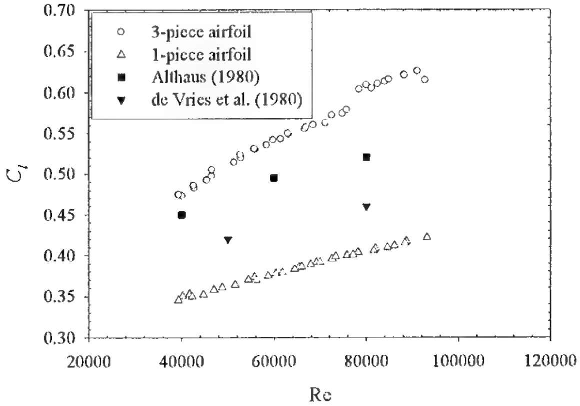
(a) Top view

(b) Individual pieces

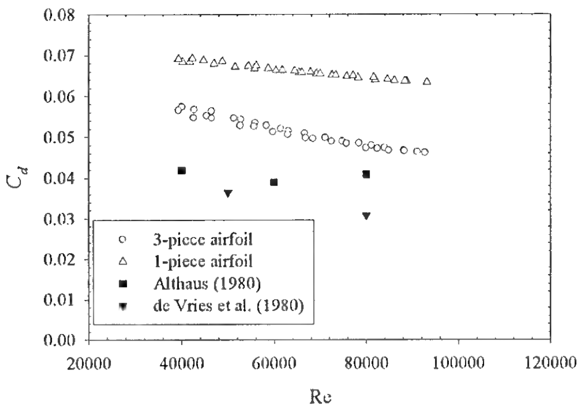
Figure 70: 3-piece Eppler 61 airfoil model tested in wind tunnel

these investigators used a strain gauge force balance to measure lift and a wake rake to measure drag. Since the drag measured with a wake rake is usually obtained at the mid-span of the model, it does not take end effects, or 3D effects, into account. These end effects can be significant at very low Reynolds numbers. Therefore, drag coefficient results from Althaus and de Vries et al. were expected to be smaller than the present results and this trend was observed.

In order to study the effect of endplates at low Reynolds numbers, Selig et al. (1995) showed how C_d can vary for a two-dimensional airfoil along the span of the model at low Reynolds numbers. Figures 73 through 76 show drag polars on an SD6060 airfoil at $Re_c = 60,000$, $100,000$, $200,000$ and $300,000$, as obtained using a wake rake with the momentum technique for C_d and a strain gauge force balance for C_l. For $Re_c = 60,000$ and $Re_c = 100,000$, the drag polars varied significantly along the span of the model, which implied a three-dimensional flow. At $Re_c = 200,000$ and especially at $Re_c = 300,000$, the drag polars were relatively constant along the span and a nearly two-dimensional flow was believed to exist.

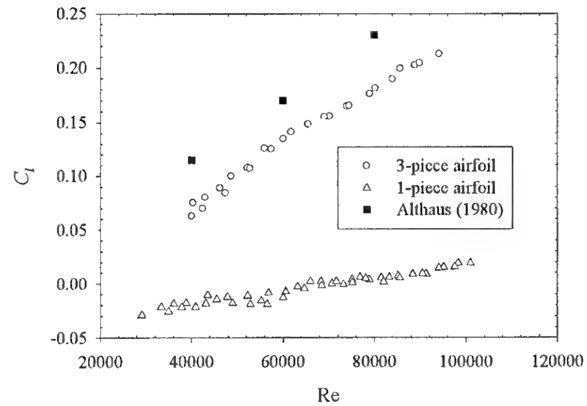


(a) Lift coefficient

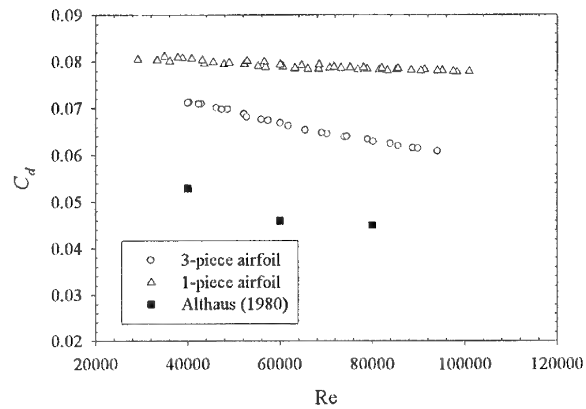


(b) Drag coefficient

Figure 71: Endplates effect on 2D characteristics of Eppler 61 airfoil at $\alpha = 0°$ with UND-FB2



(a) Lift coefficient



(b) Drag coefficient

Figure 72: Endplates effect on 2D characteristics of Eppler 61 airfoil at $\alpha = -2°$ with UND-FB2

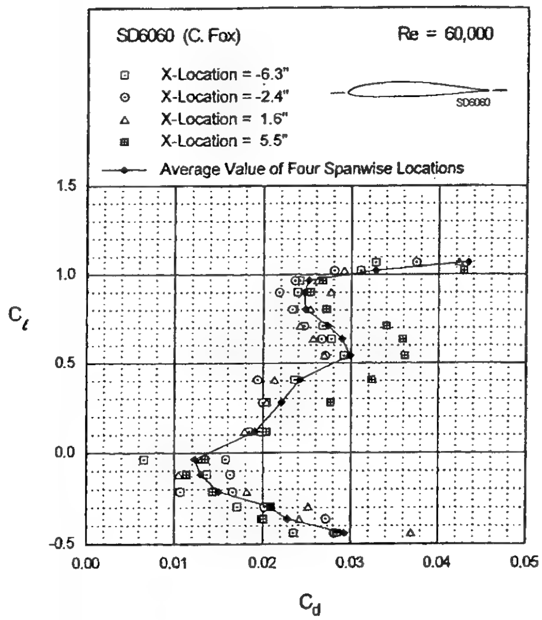


Figure 73: Drag polar for SD6060 airfoil at $Re_c = 60,000$ *(Selig et al., 1995)*

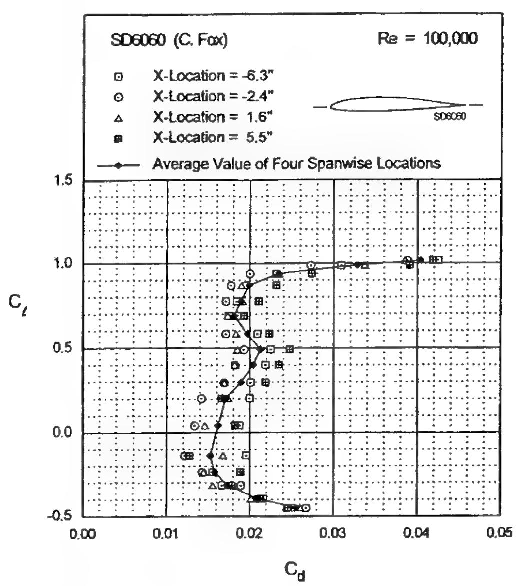


Figure 74: Drag polar for SD6060 airfoil at $Re_c = 100,000$ *(Selig et al., 1995)*

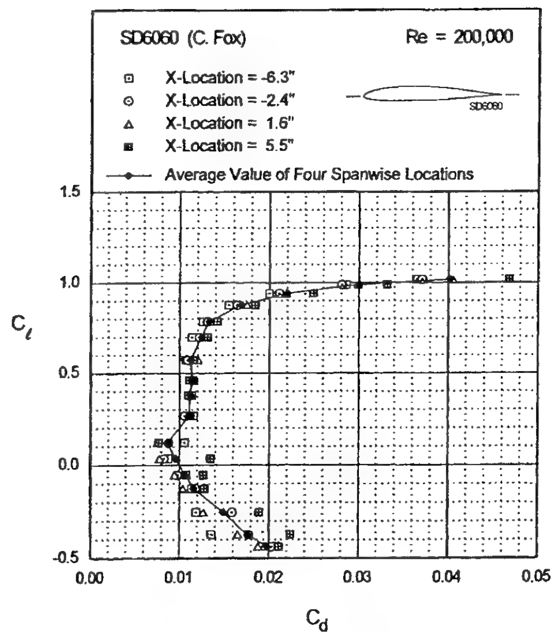


Figure 75: Drag polar for SD6060 airfoil at $Re_c = 200,000$ *(Selig et al., 1995)*

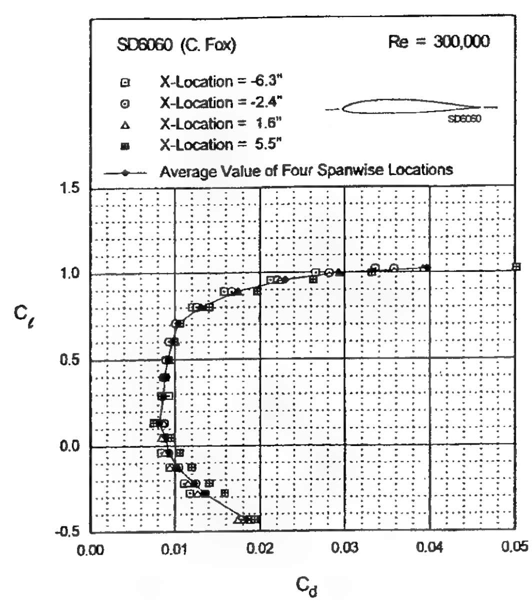
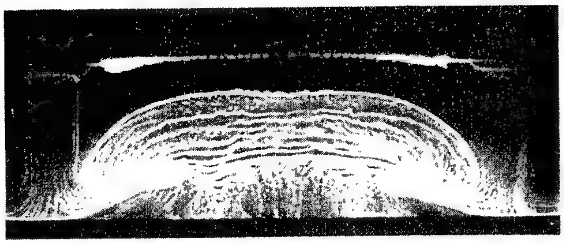
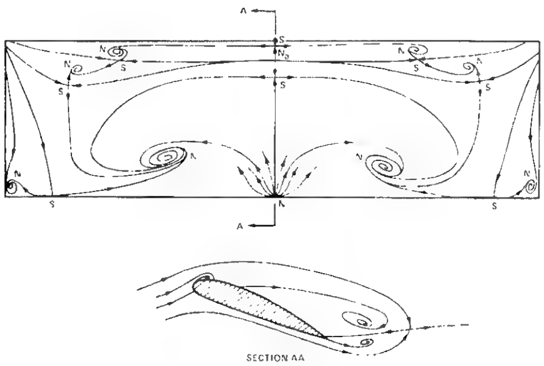


Figure 76: Drag polar for SD6060 airfoil at $Re_c = 300,000$ *(Selig et al., 1995)*

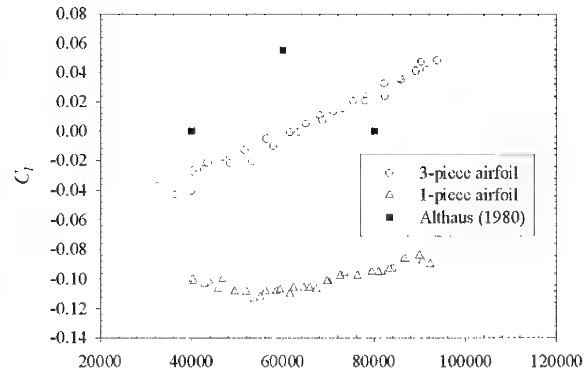


(a) Oil flow on Clark Y airfoil at $Re_c = 2.5 \times 10^5$ (Peake and Tobak, 1982)

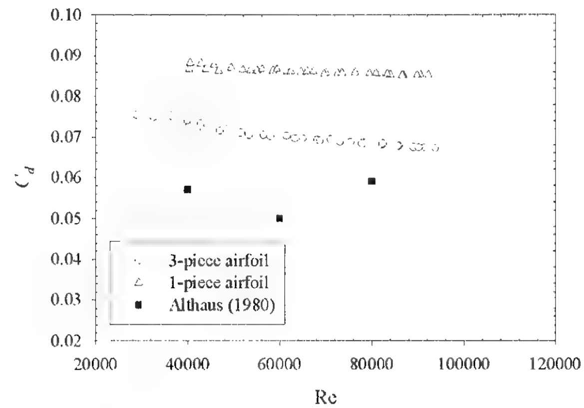


(b) Conjectures pattern of skin-friction lines (Peake and Tobak, 1982)

Figure 77: Flow pattern over a rectangular wing of aspect ratio 3.5 at angle of attack beyond stall



(a) Lift coefficient



(b) Drag coefficient

Figure 78: Endplates effect on 2D characteristics of Eppler 61 airfoil at $\alpha = -2.5°$ with UND-FB2

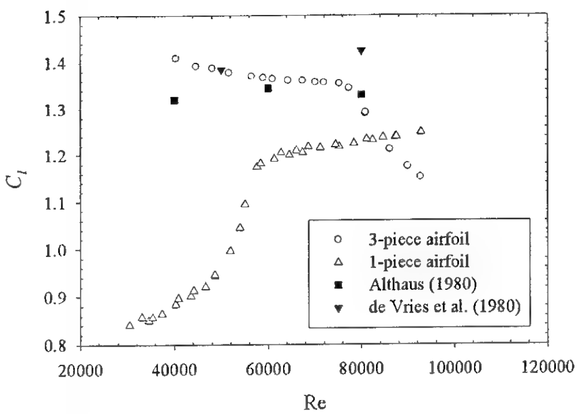
For semi-infinite models, and also for finite models, the flow is highly three-dimensional, as was shown by Williams (1996) for low aspect-ratio wings at high angles of attack and Winkelman and Barlow (1980), whose work was reviewed by Peake and Tobak (1982). Figure 77 shows the flow pattern over a finite rectangular wing at an angle of attack beyond stall.

Other results for the 3-piece Eppler 61 model indicated that the zero-lift angle of attack was close to $-2.5°$ instead of $\alpha = -2°$, so tests were conducted at the new zero-lift angle of attack, as shown in Figure 78.

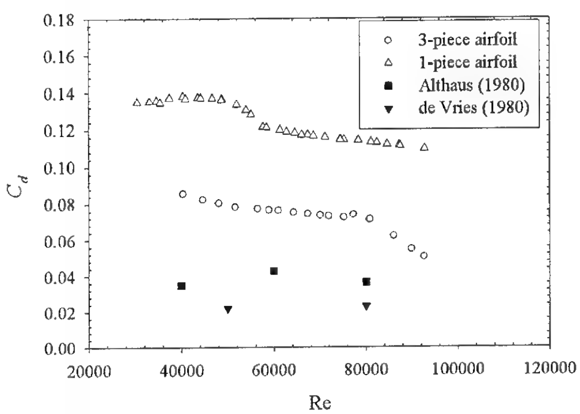
For the full model, it was determined that $(L/D)_{\max}$ occurred at $\alpha \approx 8°$. The 3-piece model was then tested at an angle of attack of 8°. Unfortunately, the lift force acting on the middle section of the model became large enough at larger Reynolds numbers to deflect the lower tip of the section, which resulted in a poor alignment with the fixed bottom part of the model. Some three-dimensional effects were then believed to be created, which yielded results that did not follow a two-dimensional trend: the lift coefficient started to decrease with increasing Reynolds number. It is known that a semi-infinite model, where the bottom endplate has been removed, will have a lower lift coefficient than an infinite model, or pseudo-infinite model. Figure 79 shows the results at $\alpha = 8°$. It is interesting to note the significant increase in C_l just before $Re_c = 60,000$. This larger lift coefficient at Reynolds numbers greater than $60,000$ was mentioned earlier when looking at the behavior of C_l with angle of attack for different Reynolds numbers.

Conclusions

It has been shown that sensitive equipment must be used to perform aerodynamic measurements on small models at very low Reynolds numbers. To achieve this goal, a new platform aerodynamic balance was designed



(a) Lift coefficient



(b) Drag coefficient

Figure 79: Endplates effect on 2D characteristics of Eppler 61 airfoil at $\alpha = 8°$ with UND-FB2

and built at the University of Notre Dame. The balance shows good sensitivity, repeatability and accuracy. Techniques to reduce noise and increase the accuracy of the results in the water tunnel below Reynolds numbers of $40,000$ are still being investigated.

Moreover, it has been shown that cambered-plate wings with 4% camber offer better aerodynamic characteristics than flat-plate wings for a given Reynolds number. Reducing the Reynolds number can lead to poor performance due to the large reduction in $\left(\frac{L}{D}\right)_{\max}$ and $\left(\frac{C_L^{3/2}}{C_D}\right)_{\max}$ for both flat- and cambered-plate wings.

The turbulence intensity in the tunnel and the trailing-edge geometry have been shown to have a very small effect on the measurements of lift, drag and pitching moment on the thin models tested in this investigation. However, the presence of endplates can affect the results for lift and drag due to the interaction between the boundary layer growing on the endplate and the flow around the wing. The presence of endplates at low Reynolds numbers reduces the 2D lift and increases the 2D drag that would normally be obtained with a truly infinite model, according to tests on the Eppler 61 airfoil. Furthermore, for a given model, adding one endplate leads to an increase in lift compared to the case without an endplate. Testing finite wing models without endplates appears to be desirable at low Reynolds numbers because it eliminates endplate effects. The full effect of the endplates is still under investigation, especially for cambered-plate wings.

Finally, trends of $C_{D_{\min}}$ versus Re_c should be investigated by fixing the wing at the angle of attack yielding $C_{D_{\min}}$ and then varying the wind velocity, hence the Reynolds number, in the tunnel. This seems to help to eliminate scatter in the results. Tests using this technique on various flat plates have indicated the expected trends of a reduction in $C_{D_{\min}}$ and an increase in C_L with an increase in Reynolds number.

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Tactical Payloads for UAVs

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Introduction

The Tactical Systems Program Office of the Program Executive Officer, Cruise Missiles and Unmanned Aerial Vehicles PEO(CU) is developing and refining Payload Concepts of Operation (CONOPS) based on demonstrated capabilities, new technology, and emerging operator needs. The Tactical Systems Program Office continues to expand technical and operational capabilities for increased Unmanned Aerial Vehicle (UAV) applications. To support future military operations, the Tactical Systems Program Office foresees UAVs as a complement to manned and space based systems.

Traditionally, UAV Payload operations focused on the ElectroOptical/InfraRed (EO/IR) reconnaissance role. While still the highest priority requirement, new technologies have expanded potential payload applications. Aware of the importance of newly maturing technologies, the Tactical Systems Program Office continuously monitors technologies sponsored by the Government and industry to determine their direct application to UAV airborne platforms and ground stations.

The following discussion addresses the Tactical Unmanned Aerial Vehicle functional priorities.

Reconnaissance Surveillance & Target Acquisition (RSTA)

A method of direct support to the battlefield commander, RSTA utilizes tactical versus strategic methods of intelligence gathering IMINT and SIGINT. Information can be gathered months, days, hours or minutes prior to battle. RSTA technology employs the following methods/equipment to accomplish the objective.

Electro-Optical/Infrared (EO/IR)

Presently, the Pioneer UAV carries either an electro-optic daylight TV camera system or a day/night infrared imaging system. To lower costs while increasing capability, reliability, and maintainability, Naval Air Systems Command (NAVAIR) Pioneer Program Office has identified a requirement for a Pioneer payload to take advantage of off-the-shelf technologies and production capabilities. This payload, DS12, (Figure 1) maximizes the use of non-developmental components to provide a sensor payload, which combines Electro-optic and infrared imaging capabilities into a single low

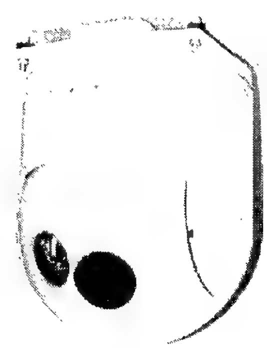

Figure 1

cost package. The Pioneer Program Office procured two prototypes and integrated them into the Pioneer UAV system. The Pioneer test team conducted six successful test flights at Webster Field, three day and three night flights. Since prototype testing proved successful, NAVAIR awarded a contract to deliver 40 units to the fleet by the end of this calendar year.

As the fleet transitions from Pioneer UAV to the Vertical Take-off and Landing Tactical UAV (VTUAV) program, the program office is considering the DS12 as the basic EO/IR payload.

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.

MICRO-CAM

The small UAV community has never had the opportunity to provide mission operations in any scenario other than daylight conditions. The MicroCam, developed under a Small Business Innovative Research (SBIR) program, provides small UAVs no-light, and camouflage penetrating daytime images. The miniature, 20.3

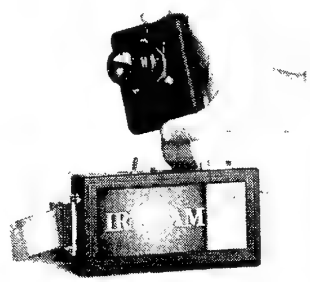

Figure 2

ounce, MicroCam infrared camera (Figure 2) produces high resolution thermal images in the spectral band of 7-14 μm. The microbolometer array eliminates cryogenic cooling and moving parts. It also reduces thermal stress, mechanical wear, and failures of the system. The MicroCam utilizes a unique infrared detector array to create the smallest and lightest camera possible. The MicroCam was integrated into the Pointer UAV for a night flight demonstration at China Lake in October 1998. The successful demonstration of the Pointer/MicroCam system in the Military Operations in Urban Terrain (MOUT) has resulted in continued support of the program in March 1999. Plans for gimbaling the system for installations into other Small UAVs are underway.

US Army Multimission Common Modular UAV Sensors

Communications and Electronics Command (CECOM) Night Vision Electronics Systems Division (NVESD) is conducting an Advanced Technology Demonstration (ATD) to identify potential designs to reduce cost and weight through commonality/modularity of hardware/software in the development of EO/IR and Synthetic Aperture Radar/Moving Target Indicator (SAR/MTI) sensors. This ATD will develop and demonstrate a common electronics package with a modular sensor to acquire either SAR or EO/IR imagery. During combat operations, users will remove and replace only front end sensors to support mission objectives.

SAR/MTI

In May 1998, CECOM awarded a contract to acquire two prototype airborne Synthetic Aperature Radar (SAR) systems (Figure 3), and two ground station elements. Delivery will occur early in calendar year 2000. An all weather imagery intelligence that also works in both day and night. It is a mature technology that is supporting Tactical platforms. The operational mode capabilities are side looking, spot and Moving Target Indication (MTI). Some disadvantages of the SAR are , it is relatively expensive, requires a large amount of processing capability and power and is more efficient when attached to fast moving vehicles. This development will leverage off previous development efforts for the Predator UAV.

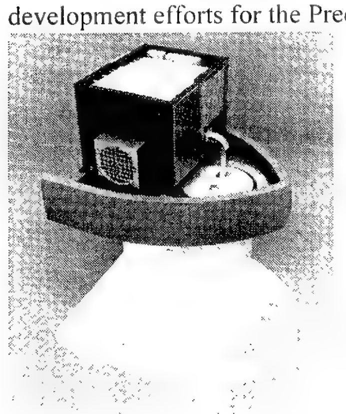

Figure 3

EO/IR

In February 1999, CECOM awarded a contract to acquire two prototype airborne units. Delivery will occur spring 2001. This development will leverage off sensor development efforts for the Predator and Pioneer UAVs.

Hyperspectral Imagery

The acquisition of images in hundreds of registered, contiguous spectral bands such that for each picture element of an image it is possible to derive a complete reflectance spectrum. This emerging technology combines

spectrometry methods with remote sensing data acquisition. It can be used for military targeting, surface composition mapping, intelligence gathering and mine detection.

ORION Wide Intercept Relay

The ORION Wideband Intercept Relay (O-WIR) offers a light weight, low cost, small volume Electronic Surveillance (ES) system that provides real time location and identification of targets for battlefield information collection and control. The O-WIR payload effectively places surveillance antennas in deep forward rear battle area providing on the move ES.

From 20 to 30 January 1997, the O-WIR UAV payload prototype was evaluated on a Hunter UAV platform. This evaluation demonstrated the operational effectiveness of a wide bandwidth RF collector mounted inside the short-range UAV. The payload successfully retransmitted the target RF spectrum to any common EW sensor asset for processing, target location, and exploitation.

The O-WIR program conducted a phase two flight test effort in October 1998. To support the additional flights a second system was purchased. The Army deemed the demonstrations as a success however, they currently have no funding line for future O-WIR efforts. There is a Merit proposal for integration of the O-WIR into a Predator UAV.

Survivor Radio Repeater System (SRRS)

To improve the search and rescue (SAR) operations of downed aviators, a need exists to develop and integrate a Survivor Radio Repeater System (SRRS) into current and future UAV systems. The existing system is limited to Line of Sight (LOS) operation and transmits a low power signal to overhead manned aircraft. The short range of these signals creates an added risk to another manned asset in the early moments of the SAR mission. The development of a low cost, lightweight repeater system for UAVs would improve the operation of survival radio systems and increase operational range by eliminating the need for LOS operations. The SRRS solution must meet technical requirements; have minimum impact on UAV performance: work in existing SAR infrastructures; and adapt to a spectrum of UAVs.

A flight test program commenced on an EXDRONE UAV in September 1998. However, due to technical difficulties, the flight test program was temporarily suspended. The program restarted March 1999. The next procurement will modify these systems to add additional frequencies to support the personnel recovery operations.

Coastal Battlefield Reconnaissance and Analysis (COBRA)

The worldwide proliferation of traditional and nontraditional mines has generated an increasingly complex and sophisticated threat to amphibious operations. The detection of mines during operations from the very shallow water/surf zone to inland is critical to littoral warfare. To enable UAVs to remotely perform beach reconnaissance for mobility assessment, the USMC has embarked on COBRA

COBRA presents a near term battlefield reconnaissance, mine detection, and image analysis system. Using a multispectral EO sensor, it detects and identifies patterned, surface and/or buried mines during daytime and limited visibility conditions. To support automatic minefield and target recognition and manual detection of obstacles and fortifications, COBRA provides Near Real Time (NRT) image processing. Pioneer UAV System integration (Figure 4) and flight-testing were completed in November 1996. All submerged minefields were successfully detected. The program transitioned from ATD status to a full acquisition program in July 1998. Risk reduction studies are underway for Marine operations and potential insertion into VTUAV.

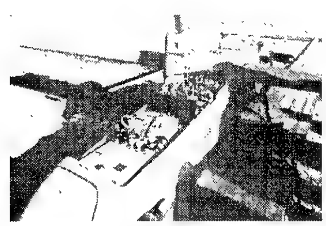

Figure 4

Tactical Dropsonde

The Naval Community is seeking improvements in the collection of meteorological data. To answer this requirement the Naval Space and Warfare Command has been developing the Tactical Environmental System (TES). TES includes the ALE family of countermeasures dispenser (CMD), minimal ALE electronics, and dropsonde canisters. The dropsonde canisters have internal sensors to collect air pressure, temperature, humidity and a GPS receiver to determine position and winds.

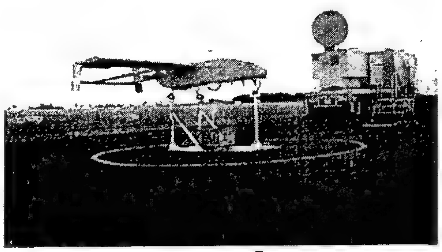

Figure 5

In the spring of 1997 this system was podded and installed on a Predator UAV. The successful dispensing and data collection resulted in the continuation of the program for a Pioneer installation (Figure 5). The Pioneer TES is a form/fit replacement for any standard Pioneer payload. The TES consists of a programmer/controller module; GPS receiver; sensor suite for measuring temperature, humidity, and barometric pressure and a 10-tube, modified ALE-47 dispenser assembly. For purposes of this demonstration, only 4 of the 10 dispenser tubes were electrically operable. Control of the TES from the ground station was accomplished via an independent 400 MHz UHF data link, which is controlled by a laptop computer. The computer also displays relevant GPS and meteorological data received serially from the TES. TES flight testing consisted of four separate flight events. The TES demonstrated the feasibility of a small, remotely controlled system to dispense a variety of expendables and link meteorological data to a UAV ground station. However, because of the failure of the T-Drop test assets, the tactical dropsonde data link portion of the TES could not be fully evaluated.

Presently the Government has awarded a contract to integrate the TES data from the pod into the Predator data stream. A follow on contract would marry the data into the Predator/Tactical Control System (TCS) interface. A production contract of T-Drops will be awarded spring 1999. To support fleet requirements, the Pioneer installation will address integration of tactical common data link (TCDL) and TCS.

Chemical Agent Detectors

Several years ago, the Defense Airborne Reconnaissance Office (DARO) hosted a series of workshops to further investigate the integration of advanced chemical sensors on UAVs. The objective was to merge practical chemical agent detection and warning systems with current MASINT technologies, advanced reporting networks, and unmanned platforms. The emphasis on UAVs is founded on the view that UAVs are unconventional platforms with lower acquisition, operational, and maintenance costs and no loss of life risk. UAVs are ideally suited to the unconventional mission of chemical detection. As a result of the contributions and inputs from all workshop participants a multiple area CONOPS was developed.

To validate aspects of this CONOPS, Central MASINT Organization (CMO) intends to execute the Chemical Agent Dual Detection Identification Experiment (CADDIE) demonstration. This demonstration will test the operational feasibility of many of the integration concepts. A CADDIE demonstration will be conducted in spring 1999 on an ALTUS UAV. The dual detection concept is supported by Chemical Dropsondes (chemsondes) and the Lightweight Standoff Chemical Agent Detector (LSCAD). The ALTUS UAV will carry both the LSCAD and the chemsonde dispenser internally. To support this flight demonstration, CMO will conduct a risk reduction flight program on a T-33.

Chemsondes are the same size as a standard MJU-10 chaff/flare canister and fit within pre-existing airborne or shipboard countermeasures equipment. The chemsondes are form-and-fit compatible with AN/ALE-47 countermeasures dispenser. This feature provides great flexibility with most combat operational aircraft.

There is a joint program to modify the LSCAD, called JS-LSCAD. The Army CBDCOM is lead on the program and has contracted for the

development of a common detector that will be an early warning chemical system for land, sea, air, manned and unmanned vehicles. The JS-LSCAD is expected to be operational in 2003.

In addition to the CADDIE program, the chemical detectors have been integrated into a Pointer UAV system. This system was flown and evaluated at the Nevada test site March 1999.

CONCLUSION

The marriage of requirements and new technology represents a symbiotic relationship. The UAV JPO attempts to match new technology with emerging requirements. Once the UAV JPO has identified the potential application of new technology, it disseminates that potential to users in the field. The process includes the acquisition and production of prototypes which hopefully leads to a production contract for delivery to operational users.

VARIOUS SENSORS ABOARD UAVs

(July 1999)

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Summary : The present paper chiefly deals with imaging sensors which could be subdivided in

* ***passive*** *ones : visible (from 380nm to 780nm) , near IR (from 0.78μ to 3μ) and thermal IR (from 3μ to 15μ) among them MWIR (from 3μ to 5μ) and LWIR (from 8μ to 12μ).*
Microwave radiometers could be of interest for demining purposes;

* ***active*** *ones : lidars and laser rangefinders and all kind of radar sensors among them the most important one: the SAR (Synthetic Aperture Radar) and its counterpart ISAR (Inverse Synthetic Aperture Radar).*

From a communication point of view, sensor typology mainly affects the ***down-link data rate.*** *Three categories of sensors may be defined on the base of different data rates:*

****Sensors featuring low information rate***
(e.g., lower than 200kbit/s) , like Meteorological, NBC, ECM sensors;

****Sensors featuring medium information rate***
(e.g., from 200 kbit/s to 10Mbit/s), like processed SAR/ISAR, compressed VIDEO/TV, compressed FLIR (Forward Looking Infra Red), uncompressed millimeter wave Radar image, Elint/ESM sensors;

****Sensors featuring high information rate***
(e.g., over 10Mbit/s), like raw SAR/ISAR, High Definition VIDEO/TV, High definition FLIR.

Because of a lack of time, we mainly restrict ourselves to the two most important and difficult imaging sensors, namely the thermal (IR) imager (described in part A) and the SAR (described in part B).

Introduction and perspectives

In order to deal with all possible UAV imaging sensors, we better choose the example of a recently introduced UAV: the General Atomics Predator UAV.

The Predator sensor **payload** includes an EO (Electro-Optical) suite, a Ku-band SAR sensor, Ku-band and UHF-band satellite communications (SATCOM), a C-band light-of-sight data link, and a GPS/INS navigator.

The Predator's SAR sensor is the Northrop Grumman (Westinghouse) Tactical Endurance Synthetic Aperture Radar (TESAR). TESAR provides continuous, near real time strip-map transmitted imagery over an 800 meter swath at slant ranges up to 11km. Maximum data rate is 500,000 pixels per second. The target resolution is 0.3meters. TESAR weight and power consumption are 80kg and 1200W respectively. A lighter weight, lower cost SAR is currently in development for Predator.

The Predator's EO sensor suite is the VERSATRON Skyball SA-144/18 quartet sensor. It consists of a PtSi 512×512 MWIR (Mid Wave IR) FLIR with six fields of view (to easily perform either detection or recognition or identification), a color TV camera with a 10X zoom, a color TV 900mm camera and an eyesafe pulsed Er: glass laser rangefinder (this Er: glass laser could advantageously be replaced by an eyesafe Er: YAG laser because YAG is a better heat sink than glass enabling a higher efficiency).
The diameter of the EO sensor turret is relatively small-35cm. The turret has precision pointing with a line-of-sight stabilization accuracy of 10μrad.

It is anticipated that high performance UAV's of the year 2010 will have a broad range of missions, including surveillance, reconnaissance, communication , intelligence gathering of threat

Paper presented at the RTO AVT Course on "Development and Operation of UAVs for Military and Civil Applications", held in Rhode-Saint-Genèse, Belgium, 13-17 September 1999, and published in RTO EN-9.

electronic emissions, target designation for weapons attacking moving targets, and communication relay.

In view of delivering better contrasted images (especially in hazy conditions), visible cameras could be replaced by near IR cameras which are less affected by the Rayleigh scattering (proportional to $1/\lambda^4$) of sunlight which is so detrimental to UV and blue light.

The biggest drawback of the SAR is the heavy and sophisticated signal processing. Presently, most UAVs are using on ground SAR signal processing requiring a high information data rate for the down-link in order to send the raw SAR data to the ground station. This is, for instance, the case for the SWIFT 1 UAV SAR (weighting about 25kg) from SAGEM. But SAGEM has a SWIFT 2 UAV SAR under development which will be able to perform real time on board SAR signal processing requiring only a medium information data rate for the down-link.

To achieve this ultimate goal of **a low-weight on board real time SAR signal processing** it is worth to notice that in recent years a new transistor appeared enabling very high speed of operation (maximum frequency in excess of 1OO GHz): the HEMT (High Electron Mobility Transistor) using the fundamental concept of QW (Quantum Well). The HEMT enjoyed already several improvements which are, in order of increasing speed of operation:

- the GaAs LM (lattice matched) HEMT
- the GaAs PM (pseudomorphic) HEMT
- the InP LM HEMT
- the InP PM HEMT

Very recently a last improvement appeared: the **metamorphic HEMT layers**. IMEC (Leuven) started the growth of such layers in 1998. These structures are identical to the ones on InP, but are now grown on GaAs substrates. With a 2 μm thick buffer layer, the 3.8% lattice mismatch between GaAs and InP can be overcome. This buffer can be either a quaternary (AlGaAsSb) or a ternary (InAlAs) compound. Of both types layers have been grown successfully at IMEC and devices based on these structures yielded typically 90% of the performance of comparable InP-based devices.

With the technique of the metamorphic layers, the advantages of GaAs substrates (availability, quality, price and robustness) can be combined with those of InP based devices (superb performance).

Unmanned air vehicles (UAVs) have their nonviolent side,too,thankfully. A new type of Lucky Lindy, the Laima UAV, became the first of its kind to cross the Atlantic, and it did so on a budget-conscious 105 liters of fuel.

Equipped with temperature, pressure, humidity , and windspeed instruments, the12-kg craft steered its way last August (1998) from St. John's, in Newfoundland, to South Uist Island, one of Scotland's Outer Hebrides. It flew the 3200-km distance in 26 hours. Sponsored initially by the Australian Bureau of Meteorology, the Laima is now being supported by weather organizations in several nations.

Micro Air Vehicles (MAVs) could provide individual soldiers with surveillance and targetting information (cfr IEEE Spectrum, January 1999, pp.73-78).Two candidate designs, initially equipped with CCD (Charge-Coupled Device) cameras, are a novel flying disk from AeroVironment Inc., in Monrovia, Calif., and a fixed-wing craft from Sanders, Nashua, N.H. The chief design hurdle, apart from the aerodynamics, is getting enough power into such small objects.

Part A.
Thermal (IR) Imager

A. 1. Thermal Imaging Devices

Like the image intensifier, the thermal imager is a *passive* night vision device being thereby *undetectable* by the opponent. But its working is independent of the ambient illuminance because a thermal imager is sensitive to the *thermal IR* radiation (composed of all wavelengths λ between 3μ and 15μ, where $1\mu = 10^{-6}$m) emanating naturally from all observed objects.

The thermal image has another aspect than the "visible" image: e.g., a white man and a black man are both seen "white" while a polar bear is seen entirely black. Consequently, we have to learn to interpret thermal images.

Because the atmosphere exhibits 2 transmission windows (cfr fig. A.1) within the thermal IR wavelengths ($3\mu < \lambda < 15\mu$), 2 kinds of thermal imagers coexist, respectively the 3μ to 5μ imager (devoted to the same window) regularly called MWIR (Mid Wave IR) and the 8μ to 12μ imager (dedicated to the 8μ to 14μ window) sometimes termed LWIR (Long Wave IR).

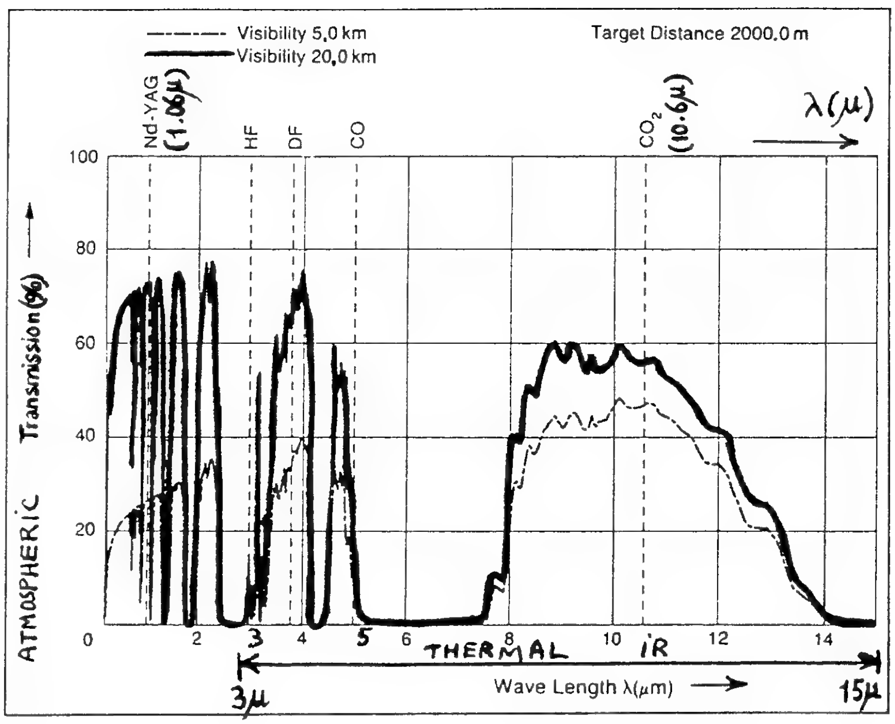
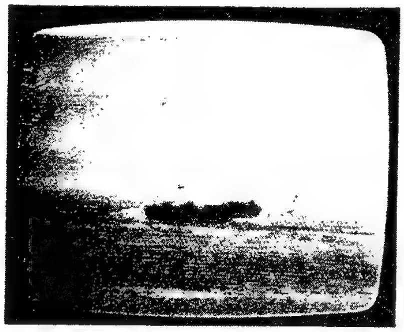
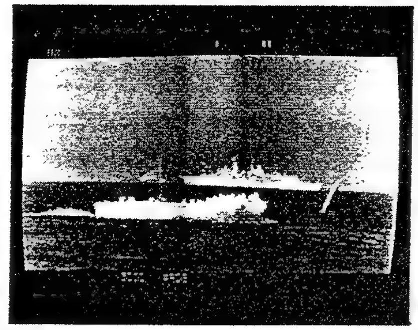


Fig.A1. Atmospheric transmission for a target distance of 2km with the wavelengths of the main lasers of military interest. The visibility distance is a distance at which a unitary contrast object is perceived with a visual contrast of 2% (which is an unvisible one because the lowest contrast perceptible by the best eye is 3%). Itis seen that only the CO_2 laser is compatible with thermal imagers (8μm- 12μm) and can penetrate mist, smoke and dustclouds.
MILTECH 5/87, p.126.



Normaal TV beeld



Thermisch TV beeld

Fig.A2. (Visible) TV image (left) and thermal image (right) taken with a Th IR camera in the (8μm-12μm) band on a hazy day in Den helder (NL). On the lefthand "visible" image, one ship is barely distinguishable at a few hundred meters from the pier. On the (righthand) thermal image a second vessel is clearly visible at 6km from the pier.

Thermal imaging allows the user to see through external visual camouflage means, smoke screens, vegetation (even heavy brush); this is called the *decamouflaging effect* of thermal imagers.

Thermal imagers in the 8 to 12μ waveband work fairly in adverse weather conditions and can penetrate moderate natural (like drizzle, haze, fog,mist) and manmade (like dust clouds and smoke screens) obscurants. This is illustrated by fig.A2.

Furthermore the maximum range of thermal imagers is about 10 times that of image intensifiers. Some FLIR's (Forward Looking Infra Red) equipping, e.g. the F-117, can probably "see" at 40km. Spaceborne FLIR's can even "see" at several hundreds of km's.

Considering all the previous advantages of thermal imaging, one could wonder why image intensifiers are still in use. The response is that, today, thermal imagers are about 5 times bulkier, heavier and more expensive than image intensifying devices.

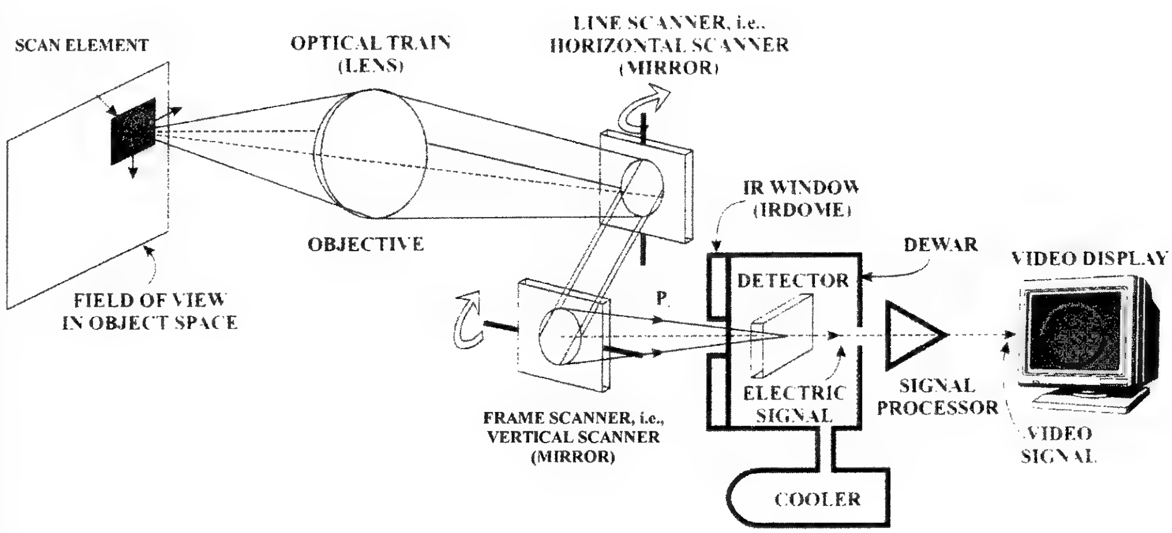


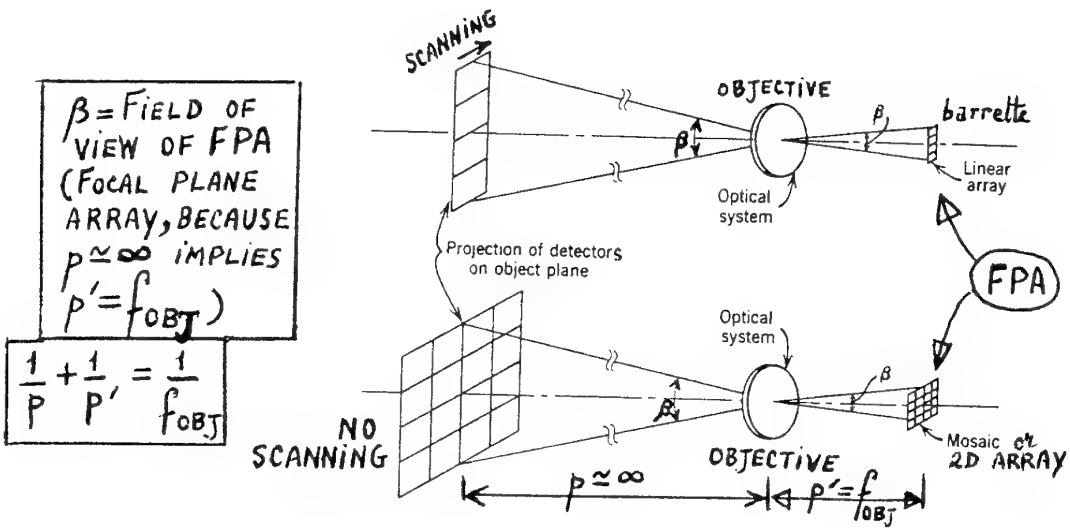
Fig.A3. Simple single-detector dual-axis thermal imager; the "*scan element* " is also often called "*resolution element* " and is nothing else but the usual "*pixel* ", i.e., it is the detector's image in the plane of the object.

Figure A3 depicts the structure of a single-detector thermal imager using a 2D optomechanical scanning as used by FLIR's. The objective is a converging system imaging the *resolution element* (which is the detector's image in the object space and corresponds to the transverse section of the radar resolution cell) of the object onto the IR detector. This detector produces a weak electrical signal which is amplified to drive a display which is electronically scanned in *synchronism* with the detector's scanning to generate a visual counterpart of the (invisible) IR image. The opto-mechanical scanning (by both scanning mirrors) of fig.A3 is difficult to ruggedize. Therefore, there is a clear evolution towards electronic scanning which is inertionless and more rugged by nature and whose first achievement was a staring array from Mitsubishi using 512×512 PtSi detectors monolithically integrated with their Si CCD readout cells. Of course, electronic scanning requires FPA's (Focal Plane Arrays) - see fig.A4 - with no mechanical scanning at all.

Real time thermal images with high temperature resolution (enabling eventually to image objects at many tens of kilometres) require a quantum detector which is made of the following semi-conductors:

- InSb or PtSi cooled at 77K (= -196°C) for the 3μ to 5μ band
- CMT (i.e., $Cd_xHg_{1-x}Te$ with $0<x<1$) cooled either at -80°C for the 3μ to 5μ band or at 77K for the 8μ to 12μ band.

The deep cooling prevents *narcissism* (explained by fig.A5 and its caption) of the quantum detector and can be performed either with Peltier elements to cool down to -80°C or with Joule-Thomson expansions or Stirling coolers to obtain 77K. Fig.A6 summarizes the main features of those three "operational" cooling mechanisms, since liquid nitrogen (T= 77K) cooling can only be used in laboratory equipments.



<u>Fig.A4. FPA (Focal Plane Arrays), i.e., multielement detectors.</u>

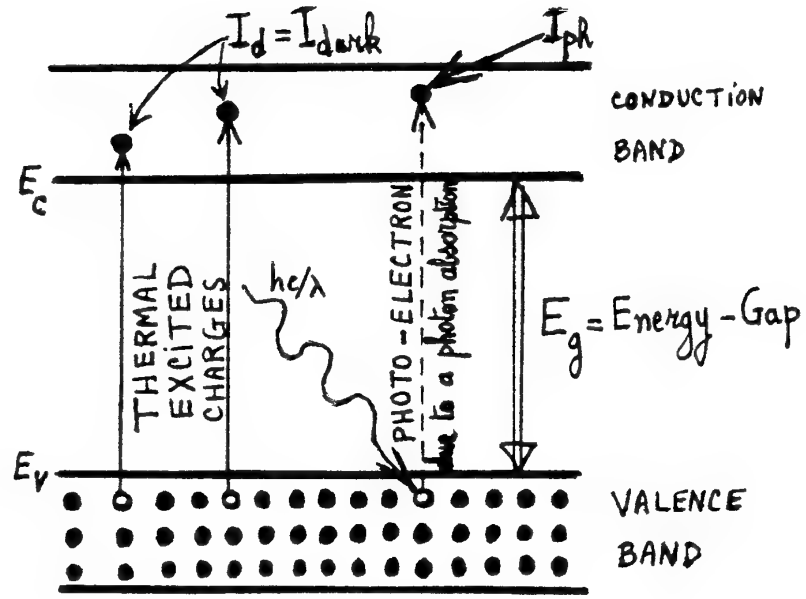
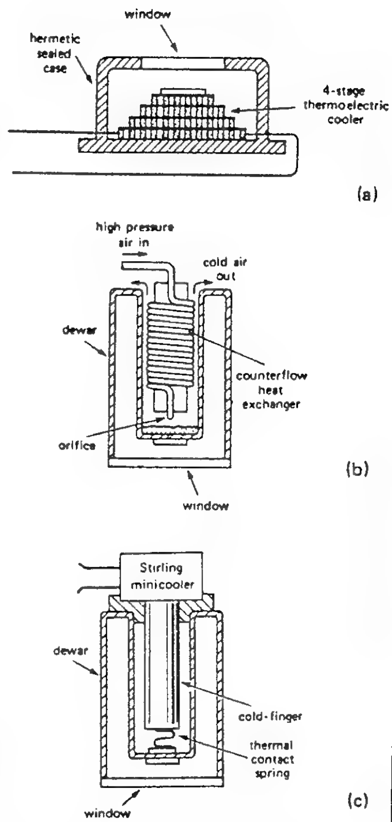


Fig.A5.Working of a semi-conductor quantum detector: an incident photon creates a hole-electron pair. Black dots represent electrons while white dots represents holes. The so-called NARCISSISM of such a detector is due to the thermal induced charges which form a dark current I_d in photo voltaic detectors while the photoelectrons constitute the photo-current I_{ph}



Three ways of cooling infra-red detectors:
(a) A four-stage thermoeletric cooler (Peltier effect) built into the encapsulation of a 3 μm to 5 μm detector, can cool it to 193 K in about 25 seconds using only a few watts;
(b) A Joule-Thomson cooler, using bottled compressed gas, can cool a 8 μm to 13 μm detector to 80 K and keep it there for as long as the gas supply lasts: one with its own compressor requires about 30 seconds cool-down time and consumes about 80 W per watt of cooling load.
(c) A Stirling-cycle engine requires about 5 to 10 minutes cool-down time to 80 K and consumes about 50W per watt of cooling load; the working fluid is helium.

Fig.A6. Three "operational" ways of cooling IR detectors.

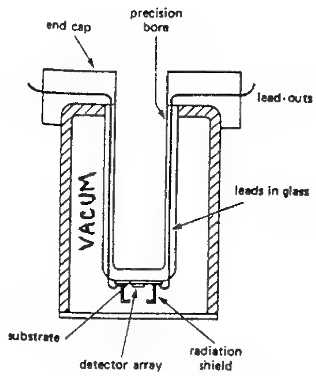


Fig.A7. Simplified cross section of DEWAR with IR detector mounted. The cold stop (or radiation shield) prevents the detector from viewing the "hot" parts of its direct environment.

Fig.A7. gives some details about the arrangement of the detector within the DEWAR.

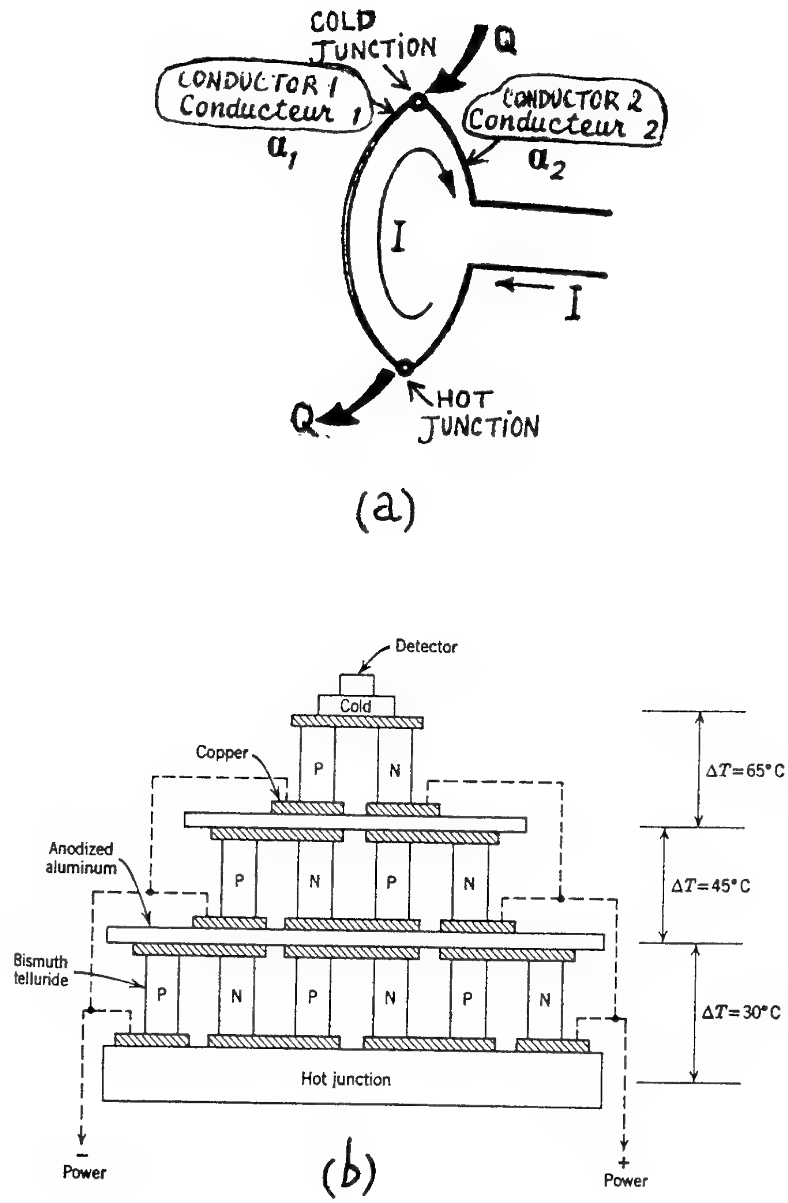
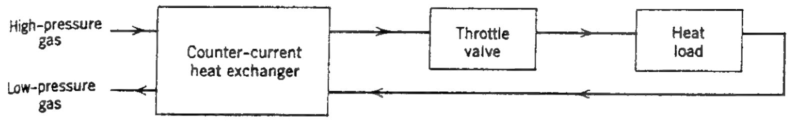
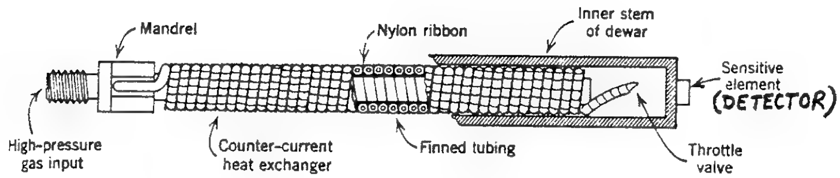


Fig.A8. Thermoelectric cooling: (a) principle of the Peltier effect; (b) three-stage thermoelectric refrigerator.

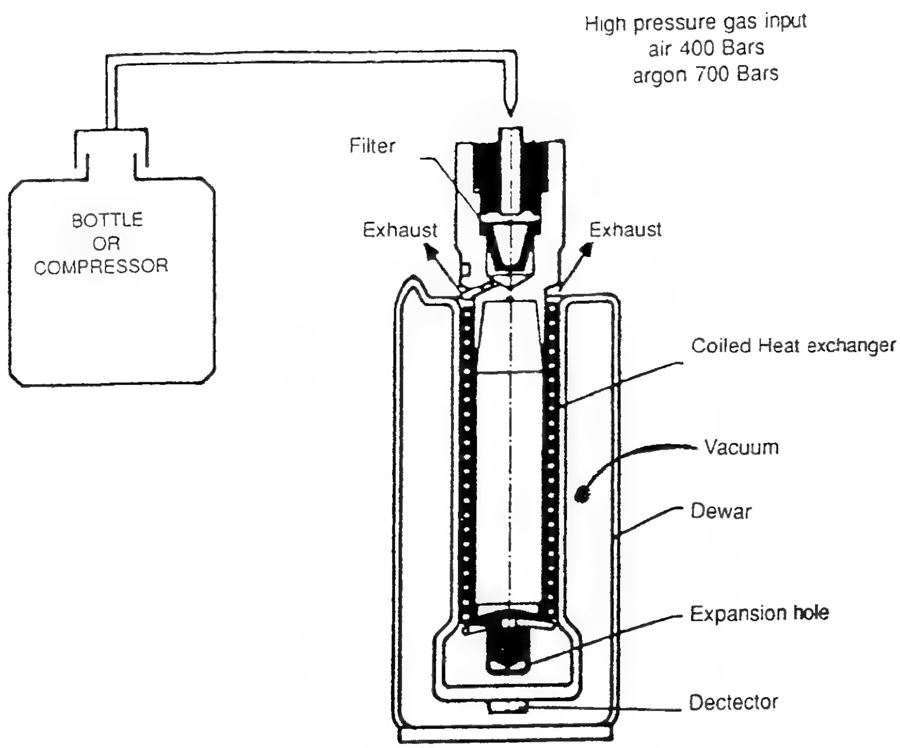
Fig.A8 (a) reminds the principle of the thermoelectric cooling by the Peltier effect while Fig.A8 (b) details a three-stage thermoelectric cooler.



(a) Schematic of Cryostat Operation



(a) Construction of a Cryostat



(b) Cooling by Joule-Thomson.

Fig.A9. <u>(a) Principle of the Joule-Thomson cryostat; (b) more details about the Joule-Thomson cooling.</u>

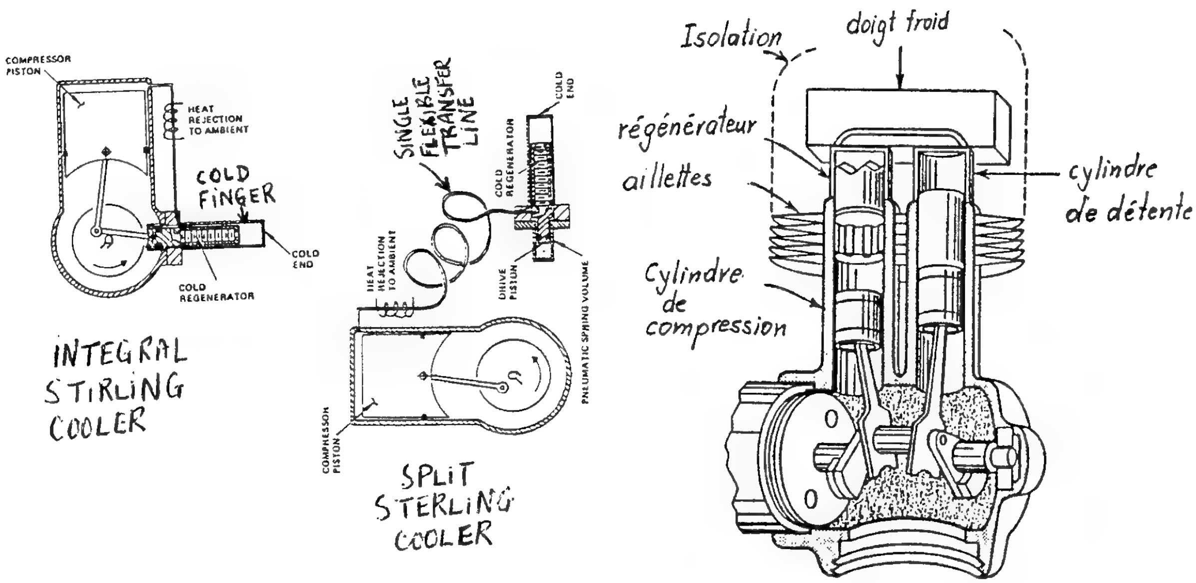


Fig.10. Views of the integral-Stirling cycle cooler (left) and the more recent split-Stirling cycle cooler (right). The latter allows the compressor to be conveniently located
[Photonics Spectra, Oct 89, p.76]

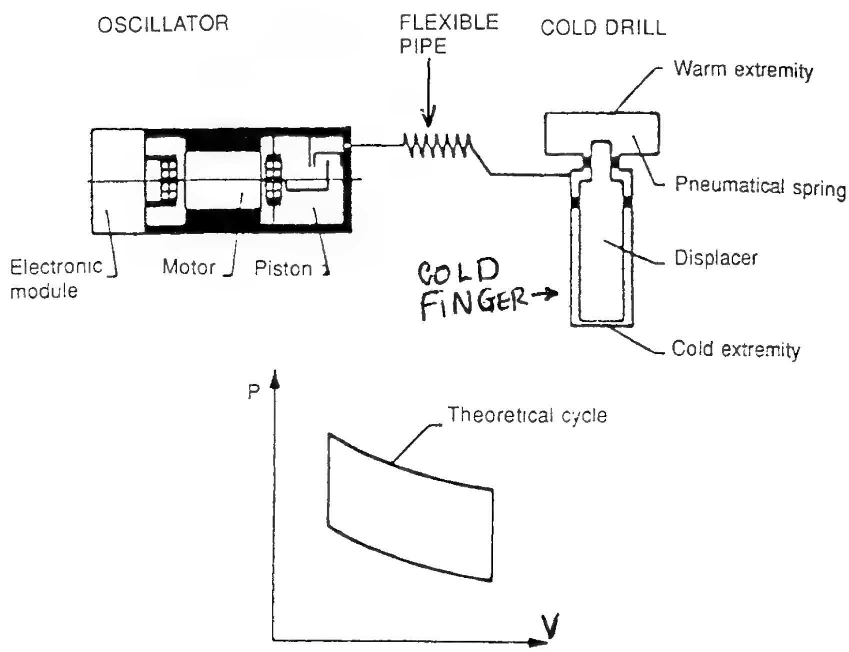


Fig.A11.Split Stirling cooler and Stirling heating cycle.

Fig.A9 explains better the cooling by a Joule-Thomson expansion of a dry high pressure gas usually contained within a bottle; for this reason this cooling method is sometimes called"bottle cooler". Figures A10 and A11 detail better the Stirling cooler. Most IR detectors exhibit also a piezoelectric effect; hence, they suffer from a microphonic noise. For that reason the previous integral Stirling coolers (cfr fig.A10) have been replaced by the split Stirling coolers in order to avoid that micropho-nic noise of the detector which rings like a bell when it is pinched.

B. 2. Physics and Investigation of Thermal Images

IR thermography is based on the thermal radiation laws (illustrated by fig.A12) established by Planck, Wien and Stefan-Boltzmann. Wien's law, expressing the wavelength of maximum radiation $\lambda_{max}(\mu) = 2898 / T\ (K)$, explains nicely why the plume (T = 800K) of a jet aircraft or a missile is best seen by a 3µ to 5µ thermal imager while devices working in the 8µ to 12µ band are ideal for thermal imaging of objects around 300K.

A thermal imager will see the power P_r radiated by the resolution element of fig.A3, i.e., it will see the product of the area of the resolution element by its radiant excitance $\varepsilon\sigma T^4$ where σ is the (universal) constant of Stefan-Boltzmann while ε is called *emissivity* .

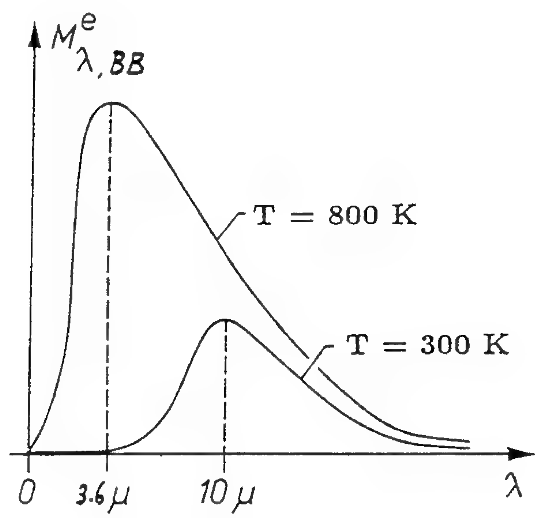


Fig.A12.Evolution of the blackbody radiation with increasing temperature

For a given imager and a given object's distance, it follows that *the thermal imager sees the product* εT^4 from *the surface of the resolution element,* i.e.the thermal imager sees heat patterns corrupted by ε which is a dimensionless factor whose values lie between 0 and 1. Emissivity can vary with the direction of measurement and it is a function of the type of material and, more especially, of the surface state of the observed material because the *thermal radiation is intrinsically a surface phenomenon.* Furthermore, for an opaque material, the emissivity is related to the material reflectance R by the equation $\varepsilon = 1\text{-}R$. The previous features explain why pleats in clothes are visible on thermal images and why a polished metal (behaving as a mirror) exhibits a $\varepsilon = 0.1$ while the same oxidized or painted metal is characterized by a $\varepsilon = 0.9$.

B. 3. Applications of IR Thermography

We are going to cite a non exhaustive list of applications (most civilian ones) of IR thermography.

(1) the search for heat leakages in buildings is obvious because a thermal imager displays heat patterns.

(2) NDI (Non Destructive Investigation) is also a straightforward application because the recording of thermal patterns (which are disturbed by hidden defects) in numerous industrial applications helps monitor potential dangers or defects, e.g., flaws in materials on a processing line can be detected.

(3) electric and electronic industry where the application is entirely based upon the heat production by Joule effect which reveals hot spots, bad connections...

(4) medical applications: is should be stressed that IR thermography can generally find breast cancer because the tumour is close to the skin.

(5) Agricultural forecast, forest surveillance, vegetation degradation and weather forecast: those applications are based on heat patterns and spatial variations of the emissivity.

(6) Archaeology: underground galleries, ruins or remains are revealed either by the decamouflaging effect or by spatial variations in the emissivity of the vegetation.

(7) Automobile: malfunctions can be found in catalytic pods, in cylinders (bad combustion), in air-filters (e.g.,stops),in exhaust gases,...

(8) Pollution: monitoring of overheating or of chemical pollution (emissivity variations)

(9) Remote sensing especially in military applications like
- revealing a tank concealed behind a heavy brush or visual camouflaging means
- revealing a squad of infantrymen crossing a field under cover of darkness.
- or even the tracks left by feet of infantrymen, this last possibility having been used, during the Vietnam war, by the US Army to detect Vietcongs concealed behind vegetation.

(10) surveillance,security, alert systems:
- sensing intrusions into hazardous or restricted areas
- thermal imagers allow harbours, docks as well as airports and high security locations to be clearly viewed in both total darkness and poor visibility.

(11) fire fighting: thermal imagers enable to find the origin of fires behind thick smoke.

(12) Rescue e.g.
- locate people overcome by smoke
- detect survivors under the debris of collapsed buildings by means of their body heat
- detect concealed bodies: this possibility has been used by the British Army in Northern Ireland to find bodies (hidden behind the vegetation) of hostages killed by the IRA (a FLIR aboard of a flying helicopter was used for this purpose)

(13) Preventive maintenance: aboard a vehicle or an aircraft, items which are going to breakdown soon can be revealed either by unusual hot spots or by cold areas, enabling to replace them in advance. British Airways and the RAF use thermal imaging to locate trapped water in aircraft structures by scanning likely areas soon after the aircraft has landed from a high altitude flight; any trapped water shows as a cold spot in the structure.

(14) Law enforcement: military IR techniques are being adapted by various law enforcement agencies to battle crime and drugs. New handheld IR imagers are replacing or supplementing image intensifiers, which are less effective, particulary for seeing through camouflage or on moonless or cloudy nights because they are light-sensitive rather than thermally sensitive, and require some ambient light to be effective.

B. 4. Thermal and Quantum Detectors

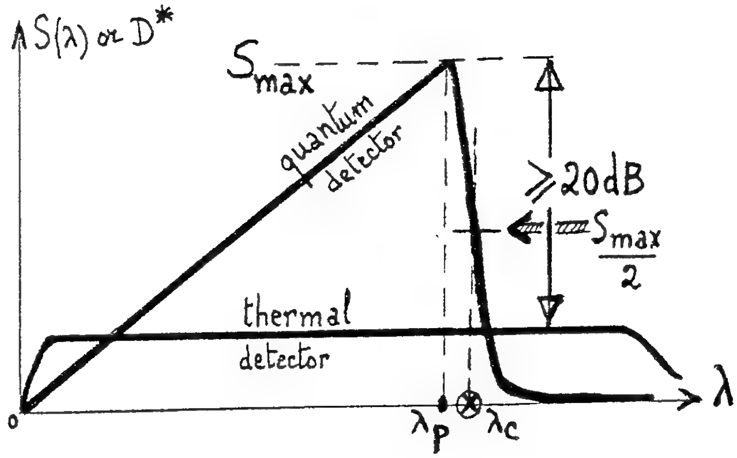


Fig.A.13. Spectral sensitivity S (λ) and specific detectivity D* exhibit the same shape for a detector. While the working of a thermal detector is almost wavelength independent, a quantum detector is much more sensitive but also strongly wavelength sensitive. Notice that $D^* = {(A.\Delta f)^{1/2}}/{NETD}$

In the case of an "uncooled" thermal imager, the detector of fig.A.3 is a **thermal detector** which may work at ambient temperature (300K) but, if compared to a quantum detector, is much slower (because of the thermal inertia) and (see fig.A.13) much less sensitive, thereby restricting the uncooled thermal imager to ranges of less than one km.

Unlike thermal detectors, **quantum detectors** are (see fig.A.13) much more sensitive (enabling high detection ranges) and faster because they use the photoelectric effect (illustrated by fig.A.5) which is a direct interaction between photon and electron.

Clearly it follows from fig.A5 that a photon

$$h\upsilon = {hc}/{\lambda}$$

can only be absorbed if its energy satisfies the condition

$${hc}/{\lambda} > Eg$$

or, equivalently, if its wavelength obeys the condition

$$\lambda < \lambda_c$$

where $\lambda_c = {hc}/{Eg}$ is the famous cut-off wavelength of a s.c. (semi-conductor) usually computed by the practical formula

$$\lambda_c(\mu) = {1.24}/{E_g(eV)}$$

Since a s.c. quantum detector can only detect wavelengths below the cut-off wavelength, it follows from the last formula and from fig.A.13 that a MWIR (3µ-5µ) imager necessitates a s.c. with a gap Eg = 0.25eV (corresponding to $\lambda_c = 5\mu$) while a LWIR (8µ-12µ) imager requires a s.c. with a gap Eg = 0.1eV which are **narrow gaps** compared to the typical value Eg ≈ 1 eV of usual s.c. like Si, Ge or GaAs. Typical narrow gap s.c. quantum detectors are InSb and CMT (Cadmium Mercury Telluride) for MWIR imagers and CMT (i.e., again $Cd_xHg_{1-x}Te$, but with another value of x because Eg and thus λ_c depend on x) for LWIR imagers.

Because of their inherent narrow gap Eg, s.c. quantum detectors feature, at room temperature (300K), a much too high value of their dark current

$$I_d = I_o \exp\left[-{E_g}/{(kT)}\right]$$

explaining their narcissism and, consequently, their requirement of a deep cooling to drastically reduce this narcissism.

Concerning the thermal detectors, we concentrate our study on the two fastest thermal detectors (enabling 25 images per second): the micro-bolometer (fig.A14) and the pyroelectric detector (fig.A15) which is a capacitor with temperature dependent dielectricum.
Unlike the pyroelectric detector (cfr fig.A16), the (micro)bolometers --which are temperature depending resistors, i.e., thermistors-- do not require that the scene be chopped, i.e., bolometers can operate with or without a chopper.

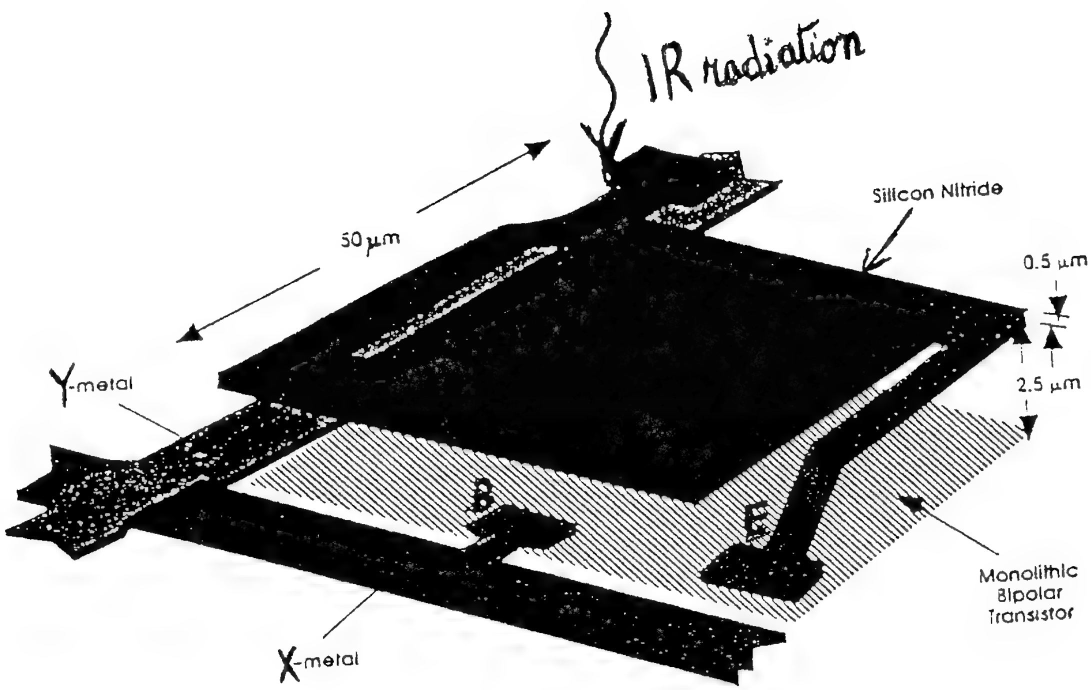


Fig.A14. <u>Honeywell's FPA structure using microbolometers which are in fact silicon thermistors</u>
[Photonics Spectra, May 94, p.44]

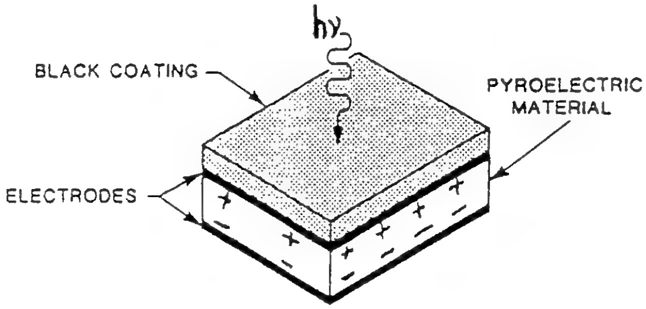
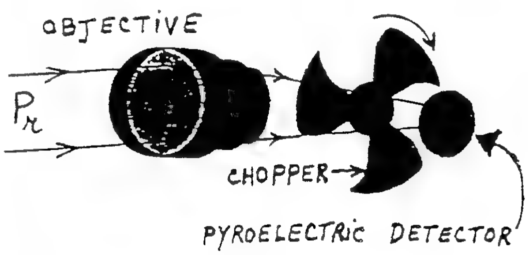


Fig.A15. A pyroelectric material has electrical polarization (permanent dipolar moment) even in the absence of an applied voltage. The materials are usually ferroelectric crystals but can be also organic polymers (like PVDF) On heating the material expands and produces a change in the polarization which builds up a charge on opposite surfaces. This causes a current to flow in the circuit which connects the electrodes. The black coating enhances the absorption of radiation and achieve (cfr fig. A13) a broad range of constant sensitivity.



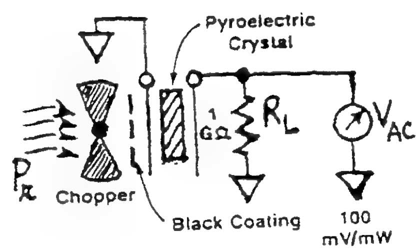


Fig.A16. Structure of a pyroelectric detecting set-up with a chopper in front of the pyroelectric detector.

We just established that a s.c. quantum detector can only "see" wavelengths obeying

$$\lambda < \lambda_c$$

This condition can be overcome with GaAs (although $\lambda_c = 0.87\mu$ for GaAs) by resorting to QWIPs (Quantum Well Infrared Photodetector) whose working is explained by fig.A17 and its caption; in the case of a QWIP, the cut-of wavelength λ_c is given by

$$\lambda_c(\mu) = {}^{1.24}\!/\!_{\Delta E}$$

where $\Delta E - \Delta E$ is the energy separation between the single bound state E_{e1} and the continuum of the conduction band-can be as low as O.1eV by a proper choice of the quantum well thickness t and the composition x of $Al_xGa_{1-x}As$

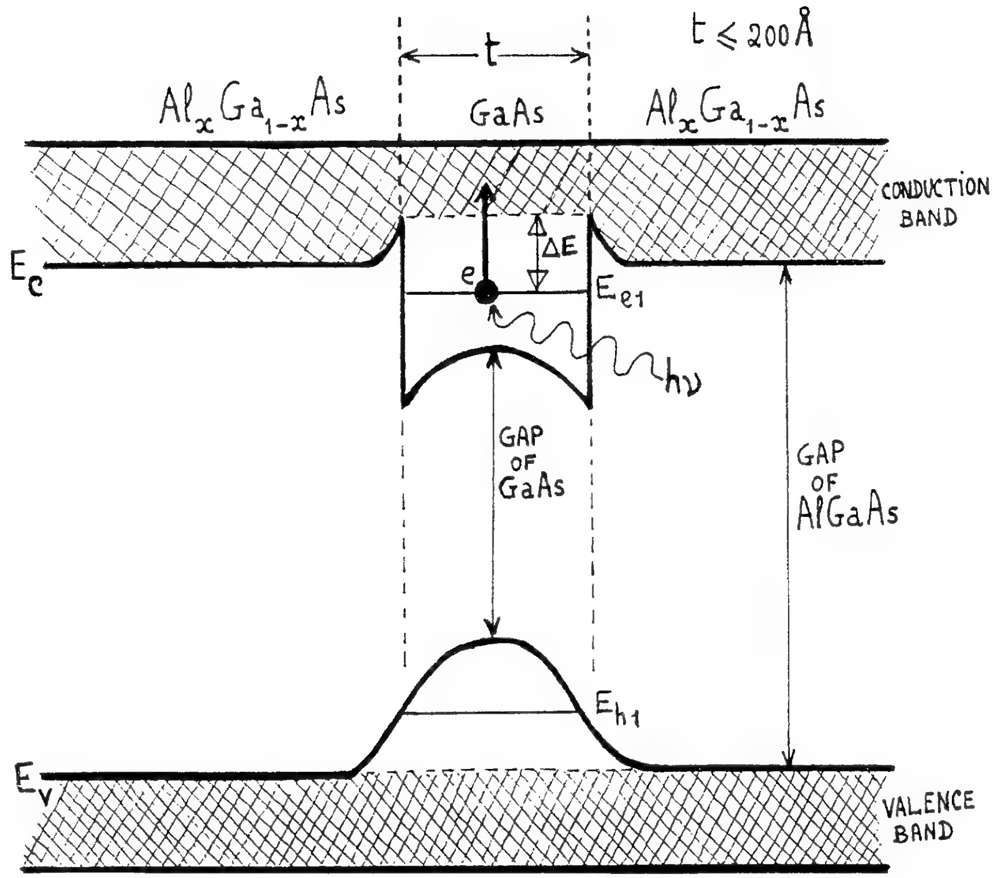


Fig.A17.Stucture and working of a QWIP. The continuum of energy levels is represented by the crosshatched areas. The QW detector uses **intraband** absorption instead of the inter-band absorption used by conventional detectors. The realization of the QW (Quantum Well) requires a well tickness t less than the de Broglie h/p wavelength which is 20nm for electrons within GaAs.

B. 5. Staring Arrays for Electronic Scanning

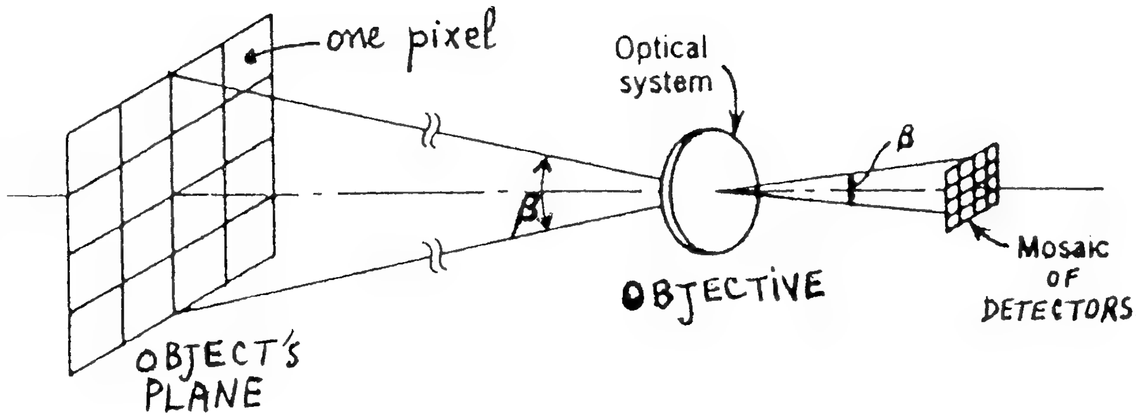


Fig.A18. A (two-dimensional) mosaic of detectors needs no mechanical scanning if its image on object's plane covers the whole FOV β of the imager: that is the definition of a staring array.

The opto-mechanical scanning of fig.A3 is difficult to ruggedize and suffers also from its mechanical inertia. Therefore, there is a clear evolution towards **electronic scanning** (comparable to phased arrays in radars) which uses special FPAs (Focal Plane Arrays) called **staring arrays**, i.e., large 2-D detector arrays which can *stare-out* into the scene giving a one-to-one correspondance (cfr fig.A18) between each pixel or scan-element (image of one single-element detector of fig.A3) and each single-element detector , which is similar in many ways to the CCD detectors used in modern lightweight TV cameras (F: camescopes). Indeed by using a mosaic, that is a 2-D array (fig.A18)
of detectors, it may be possible to cover the whole FOV (Field of View) of the imager in the object field, as depicted by fig.A18, without any mechanical or optical scanning motion provided the mosaic is big enough and comprises enough (typically, at least 512×512) single-element detectors in order not to waste the spatial resolution of the thermal imager. A staring array eliminates the expensive and tricky high-speed opto-mechanical scanning used in present thermal imagers by matching one detector to each picture element (or pixel) resulting in a compact unit which can be easily carried and used by one man.

To perform a pure electronic scanning, it "suffices" to **sequentially** read the output electrical signals of all detectors of the mosaic of fig.A18. This sequential read-out is achieved by a 2-D multiplexer which is composed either of CCD readout cells or of CMOS switches as illustrated by fig. A19.

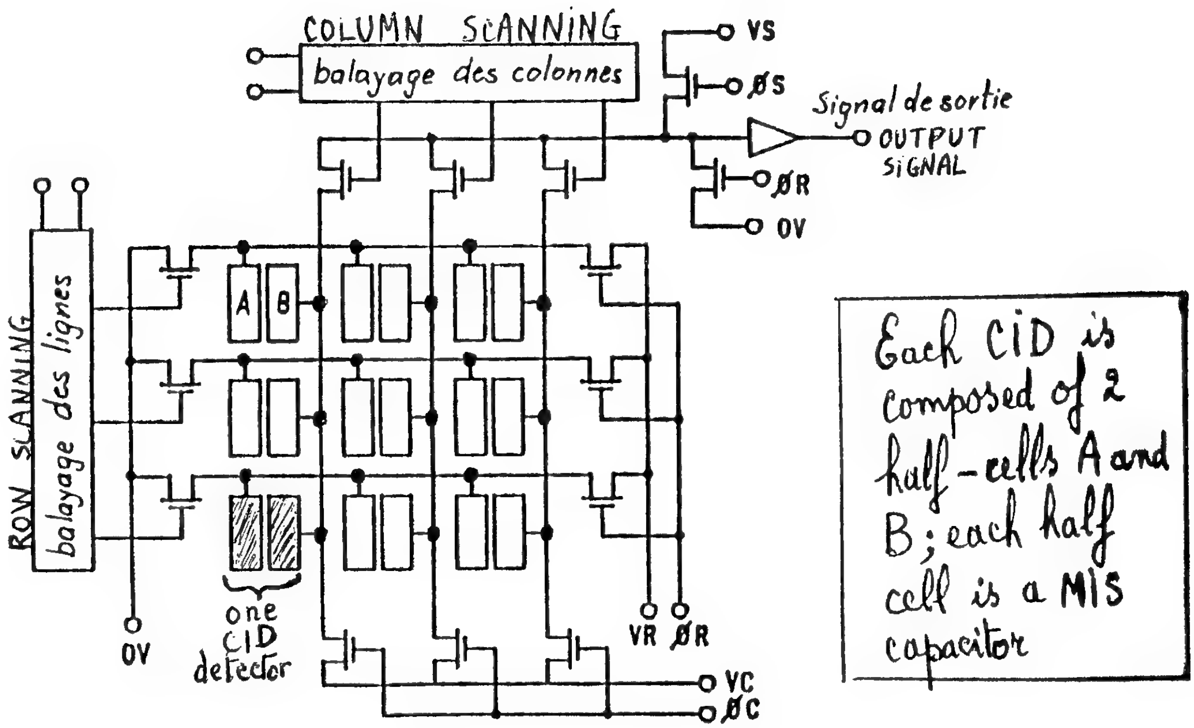


Fig.A19. Multiplexer composed of CMOS-switches for the sequential readout of 2-D array of special IR detectors called CID detectors.

Unfortunately, because of technological maturity, **most multiplexers are presently made of silicon which is lattice mismatched with most narrow gap s.c. quantum detectors,** thereby preventing monolythic integration (in one single plane) of the IR detectors and their corresponding Si readout cells. Since IR detectors like InSb and CMT are not compatible with Si, they require a **hybrid** integration (represented by fig.A20) with the additional difficulty that the whole device of fig.A20 has to be cooled inside the DEWAR of fig.A3 and that the thermal expansion coefficients of InSb and CMT are quite different from those of Si or GaAs. As illustrated by fig.A21 the same situation prevails for the microbolometer and pyroelectric detectors; fortunately the latter may work at room temperature, thereby eliminating the difficulty of the thermal expansion coefficient.

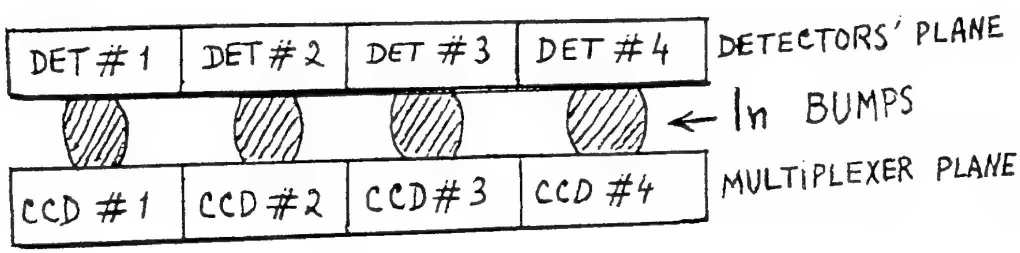


Fig.A20. Hybrid integration for InSb and CMT detectors

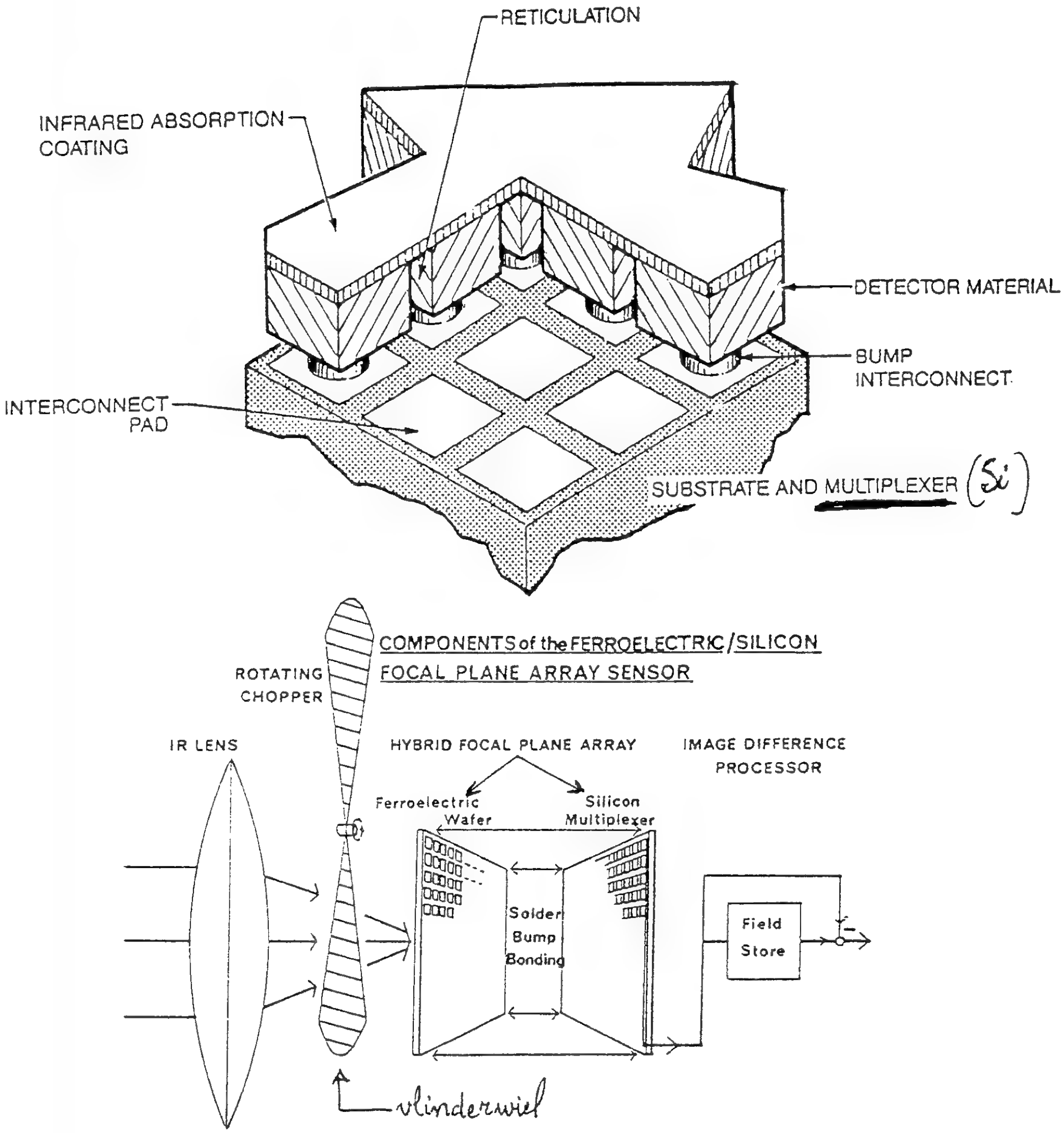


Fig.A21. Schematic of the Ferroelectric / Hybrid Focal plane Array and its use in an IR sensor head.

Recently, new thermal detectors appeared enabling monolithic integration with their readout multiplexing cells. Those detectors are arrays of micromachined thermal sensors allowing "uncooled" IR detection in the 8μ-12μ band: **the polySiGe material used as thermistor is CMOS compatible** in contrast to existing microbolometers. Imaging arrays are under development at IMEC (Leuven) as an extension of this technology.

B. 6. The Future of Thermal IR Detectors

The next considerations are coming from SPIE, OE Reports, Nr 184, April 1999.

At present, four main IR detector technologies claim the lion's share of global development: mercury-cadmium-telluride (HCT or MCT), indium antimonide InSb, quantum-well IR photodectors (QWIP) and microbolometer / pyrometer FPAs (Focal Plane Arrays). Development within these different techniques takes many tracks, from the enlarging of array sizes to the reducing of pixel dimensions; from the movement of hybrid bump-bonding designs (cfr fig.A20) to the unity of monolithic detectors and expanded spectral sensitivity in multiple colors, e.g., **bi-color or bi-spectral FPA, combining either MWIR with LWIR or NIR (near IR) with LWIR.**

InSb, which has been around for more than 40 years, represents a mature technology for imaging MWIR (3μ-5μ). "Either InSb or MCT is highly reproducible right now", said Paul Norton of Raytheon. Later this year (1999), Raytheon will release the first 2052×2052 InSb FPA for a consortium of astronomers, giving them four times the output of the previous 1024×1024 arrays.

According to Kozlowski, Rockwell is working with Boeing on dual-color devices for two-color uncooled NIR and LWIR imaging. Using InGaAs arrays for NIR and 220×340-pixel microbolometer arrays sensitive to 24mK for the 8μ to 14μ spectrum, these systems offer something special for military defense systems.

"Two-color is starting to become a very big area. With ships the short band (NIR) lets you see missiles at long ranges. A second, longer spectral band (LWIR) lets you discriminate between missiles and flares or other countermeasures", Kozlowski said.

According to microbolometer expert Paul Kruse, cutting-edge microbolometers are striving to reduce the current pixel size from 50μ square to 25μ. Parallel to this is the DARPA goal of achieving a noise equivalent temperature difference (NETD, sometimes called temperature resolution) of 10mK. "It is very hard to combine a smaller pixel size with a lower NETD because NETD goes inversely with area", explained Kruse. Notice that the specific detectivity D* has therefore been defined as

$$D^* = {(A.\Delta f)^{1/2}}\Big/{NETD}$$

where A is the detector's area (always in cm^2) and Δf is the processing bandwidth (in Hz).

Researchers are taking several different tracks towards achieving more sensitive detectors, including switching from different combinations of the active materials in the vanadium oxide (VOx) group sputtered on a silicon nitride microstructure layer, to photo-enhanced chemical vapor deposition of amorphous silicon. Other exciting areas include the high temperature resistance coefficient of colossal magneto-resistance films and new structural designs using barium-strontium-titinate (a ferro-electric material) active-area pixel arrays.

Next to the interesting material development in microbolometers lies the development of QWIP technology based (see fig.A17) on GaAs / AlGaAs heterostructures. Using MBE (Molecular Beam Epitaxial) growth on large wafers, H.C.Liu of the National Research Council Canada (Ottawa) expects that QWIP technology will lead to the most easily mass-produced IR imaging devices in the mid- to longwave IR.

Furthermore QWIPs enable an easy manufacturing of bispectral FPAs.

Both the Jet Propulsion Laboratory (Pasadena,CA) and Lockheed Martin (Sanders, NH and Orlando, FL) have two-color focal plane arrays based on QWIP designs in the 3- to 5- and 8- to 12-μm spectrum. Although QWIP designs promise to eventually reach out to 20 or 30μm, most QWIP arrays require extensive cooling down to 70K, although recent developments at Thompson-CSF show that the devices can operate at the higher temperature of 90K.

Liu expects that exploration into combining QWIPs with GaAs multiplexing circuits will increase the utility of QWIP technology by placing both detector and readout circuit on the same chip.

Another solution, being developed at the NRC Canada,involves attaching LEDs directly to the

QWIP active area and optically reading the output with a separate charge-coupled device (CCD) chip.

Interestingly, work on IR imagers has also lead to improved visible CMOS imagers. According to Kozlowski, Rockwell's work on IR imagers at Newport Beach, CA has led to the recent spin-off of a new company that has a CMOS imager of comparable or better performance than off-the-shelf CCD imagers. According to Kozlowski, the newcomer, Conexant (Newport Beach, CA), has recently announced a visible CMOS camera on a chip with 1280×1024 pixels that has a read noise below 10 e and a sensitivity of 1.5V per lux second with a dark current of 50 pA/cm^2.

Part B

The SAR (Synthetic Aperture Radar)

B. 1. Introduction

The SAR is chiefly a pulse SLAR (side looking airborne radar)-see fig.B1-performing ground imaging and achieving much better resolution (smaller pixel) on the ground through a sophisticated signal processing. The SAR is either space-borne (aboard a satellite) or airborne (aboard an aircraft), i.e., the SAR platform is either a satellite or an aircraft.

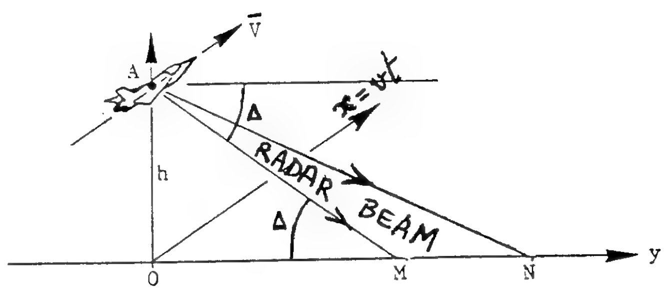


Fig. B1
SLAR with the depression angle Δ.

Motion of the SAR with respect to the ground is mandatory. The SAR requires recording of both amplitude and phase ; therefore the SAR can be claimed as being a holographic radar.

The SAR is an imaging radar achieving a pixel size comparable to that of the best EO (electro-optical) sensors which are camera's using visible and near IR radiation or thermal imagers, but the SAR is much more expensive then those EO sensors. Why then using a SAR ? Because the SAR performs much better at night, during bad weather conditions and, especially, through clouds, although the heavy signal processing does not always enable the SAR to deliver images in real time.

Indeed, Fig. B2 demontrates clearly that EO sensors are ineffective through cloud cover, while radar sensors have good to superior performance through cloud cover and rain. EO transmission through rain is a function of the size of the raindrops, rainrate and the path length through the rain. EO passive sensors are limited from about 2 to 5 km of path length through rain.
The best sensors in looking through clouds and rain are radar sensors. Radar sensors have negligible attenuation at frequencies below 10 GHz. That's the reason why most SAR's are working in the following radar bands :
L (1 - 2 GHz), S (2 - 4 GHz), C (4 - 8 GHz), X (8 - 12 GHz).
At higher frequencies, millimeter wave sensors operating in clouds and rain are limited from about 2 to 5 km length of path through the clouds and rain, with the same implications as those discussed for the EO sensors (both passive and active, like the laser rangefinder).

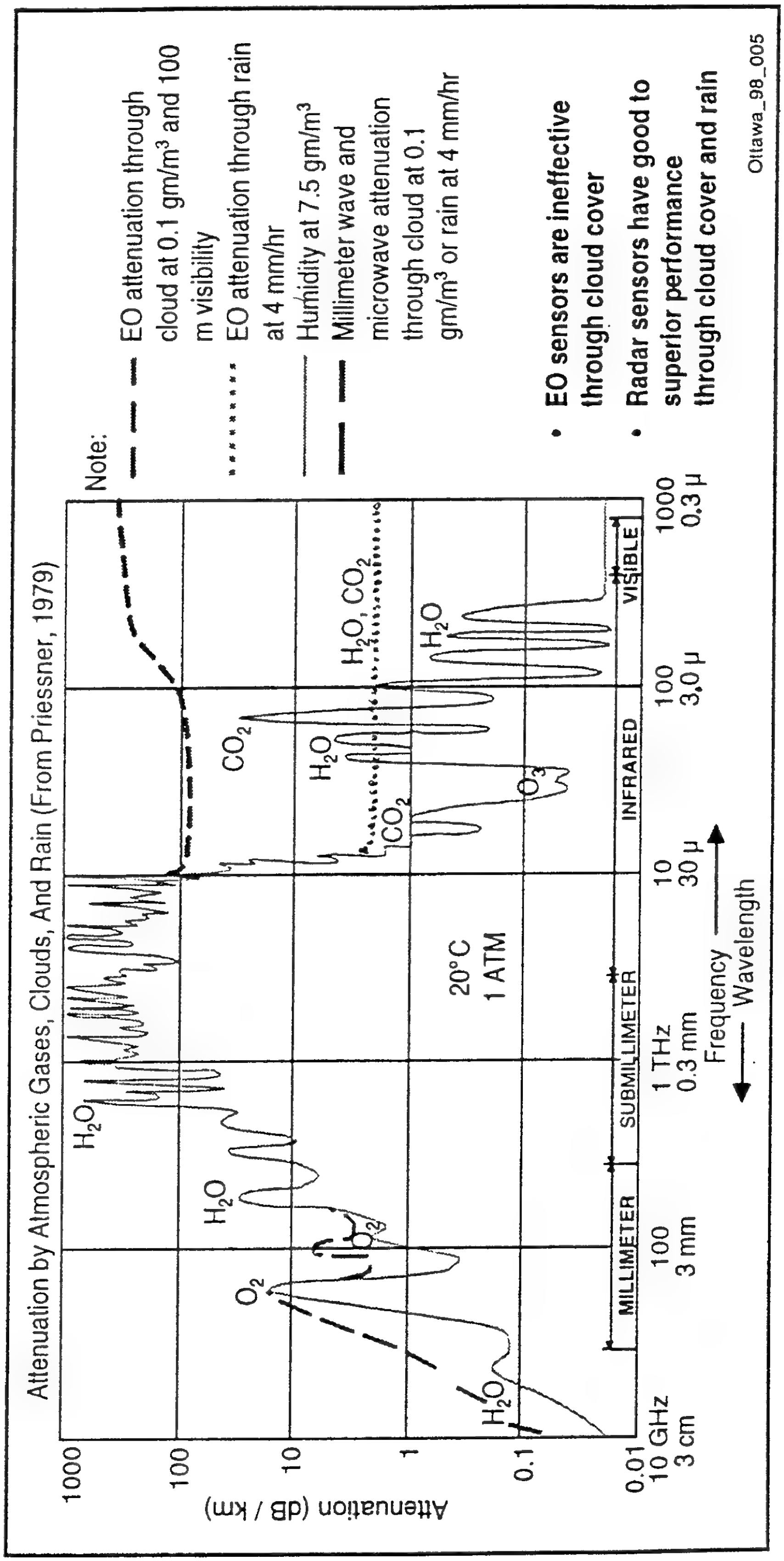


Fig. B2. Signal Attenuation Due to Weather (RTO-MP-12, AC/323 (SCI) TP/4)

The superiority of the radar (with respect to the EO sensors), which is already obvious in the presence of rain, becomes enormous in the presence of clouds. Indeed, for a 1 km length of path through a dense cloud, the 2-way (round trip) attenuation

- is 0.2 dB below 30 GHz
- is more than 200 dB for near IR and visible radiations.

Figure B3 (showing a space-borne SAR aboard the Space Shuttle) reviews the basics of SAR image formation, stressing the necessity of the platform motion for the building up of a radar image, and introduces the two image dimensions as being

- range (across-track)
- azimuth (along-track) with azimuth coordinate x. Let us now consider the image pixel, i.e., the smallest resolvable object on ground.

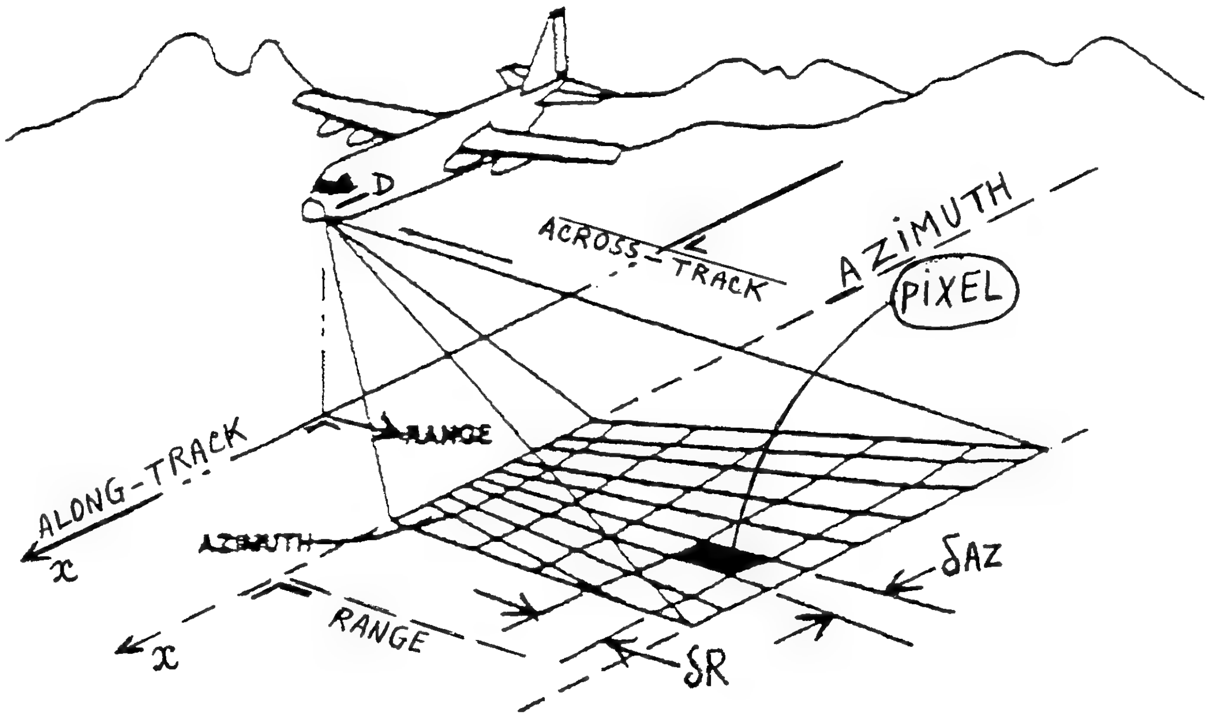


Fig. B4. The pixel of the radar image on ground with size $\delta R.\delta AZ$ (pixel = smallest resolvable object)

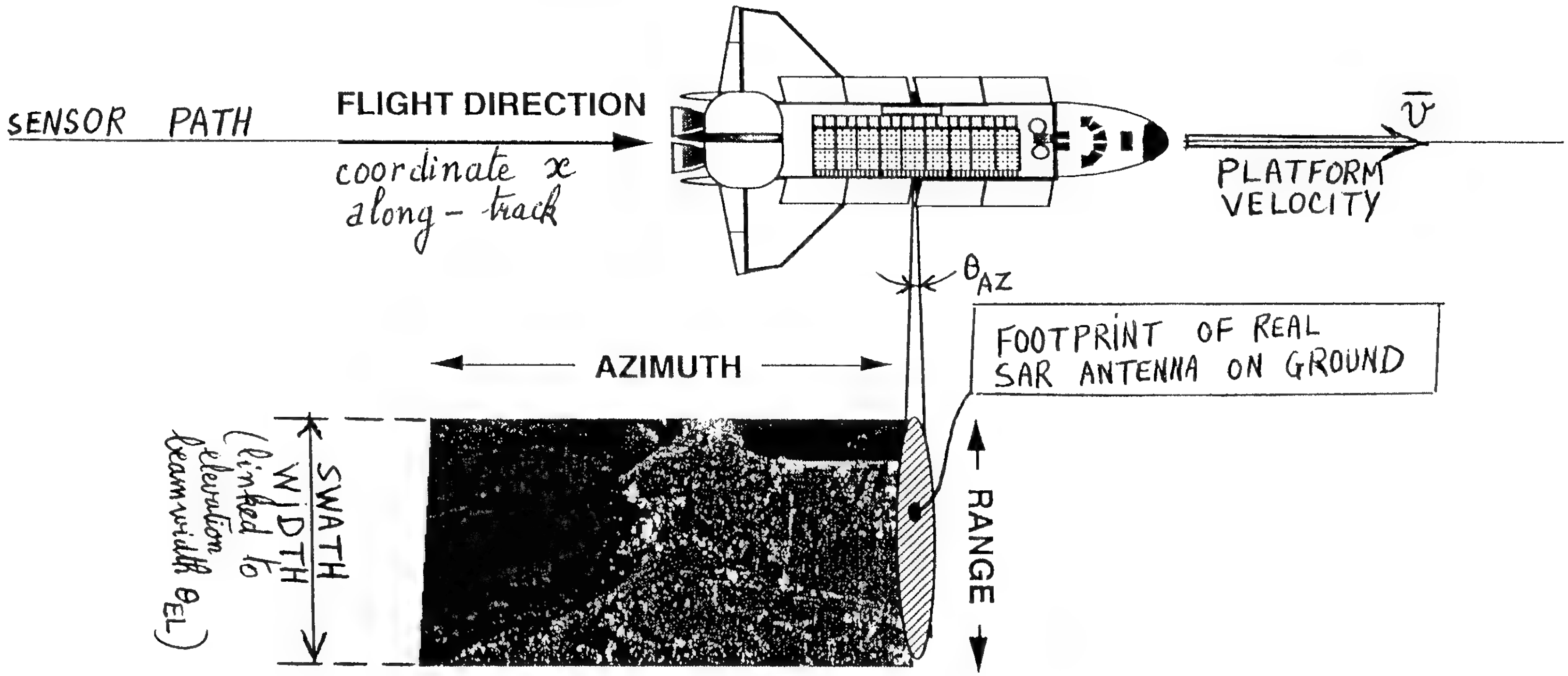
To understand the necessity of the platform motion and the subsequent signal processing of a SAR, it is of utmost importance to evaluate the size $\delta R.\delta AZ$ of the radar image pixel on the ground where (see fig. B4)

- δR is the range resolution (on ground)
- δAZ is the azimuth resolution (on ground).

The radar image pixel of fig. B4 is nothing else but the footprint on the ground of the resolution cell (fig. B5) determined by the radial resolution $c.T/2$ (where T is the pulse width) and the two angular resolutions θ_{AZ} and θ_{EL} (being respectively the 3-dB beamwidths in the azimuth and elevation planes) as sketched by fig. B5

FIG. B3. REVIEW OF SAR IMAGE FORMATION

- **BUILDING UP A RADAR IMAGE USING PLATFORM MOTION**



- RADAR BEAM ILLUMINATES A SWATH ON THE GROUND (SWATH ≡ FAUCHEE in French)
- IMAGE DIMENSIONS ARE RANGE (ACROSS-TRACK) AND AZIMUTH (ALONG-TRACK)

(the volume of this resolution cell being $^{cT}\!/_{2}.R\theta_{AZ}.R\theta_{EL}$ which is proportional to the square of the range R)

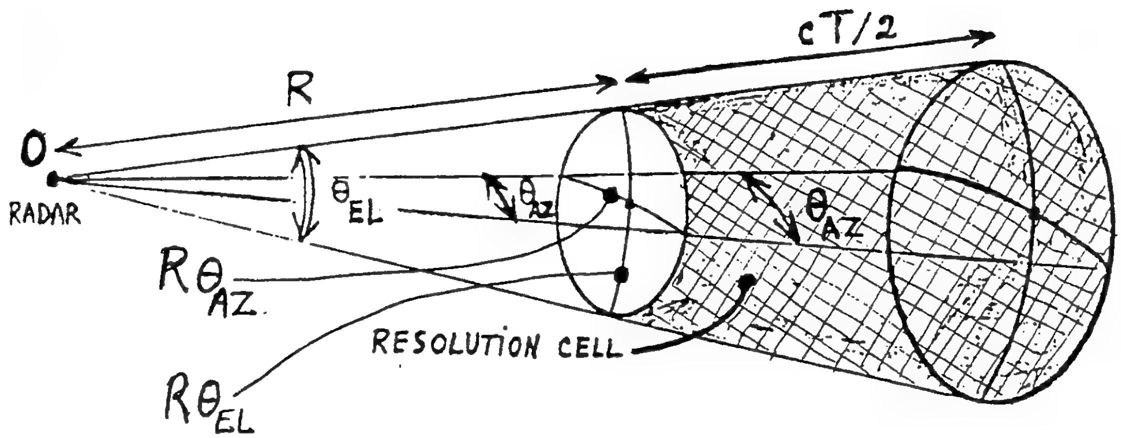


Fig B5. The resolution cell with its radial size $^{cT}\!/_{2}$ (where T is the pulse width) and its transverse sizes $R\theta_{AZ}$ and $R\theta_{EL}$

Let us first calculate the ground image pixel sizes δR and δAZ for a conventional SLAR, i.e., a radar which does not implement the sophisticated signal processing of a SAR. Therefore we introduce (see fig. B6) the coordinates used in the SAR theory, i.e., the x coordinate along track and the (slant) range R whose minimum value R_0 is the range at closed approach, i.e., when the target is purely broadside ; fig. B6 shows the azimuth angle AZ as well.

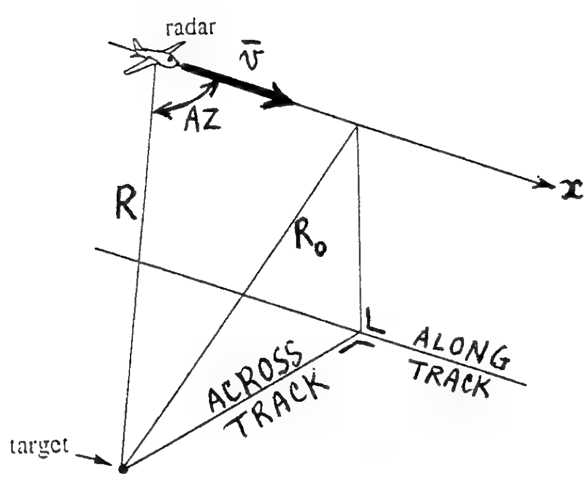


Fig. B6. SAR co-ordinate system

The range resolution δR on ground, i.e., the smallest resolvable object across track, is derived from the radial resolution $\underline{cT/2}$ by using fig. B7 which shows immediately that $\delta R = \dfrac{cT}{2\cos\Delta}$ where Δ is the depression angle ; Δ is also the grazing angle.

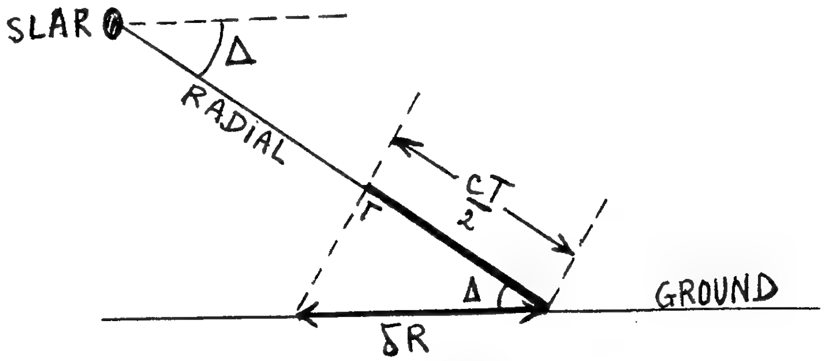


Fig. B7. <u>Derivation of the range resolution on ground</u>

To compute the azimuth resolution δAZ on ground, i.e., the smallest resolvable object along track, it suffices to calculate the transverse size $R_0\theta_{AZ}$ of the resolution cell as shown by fig. B8.

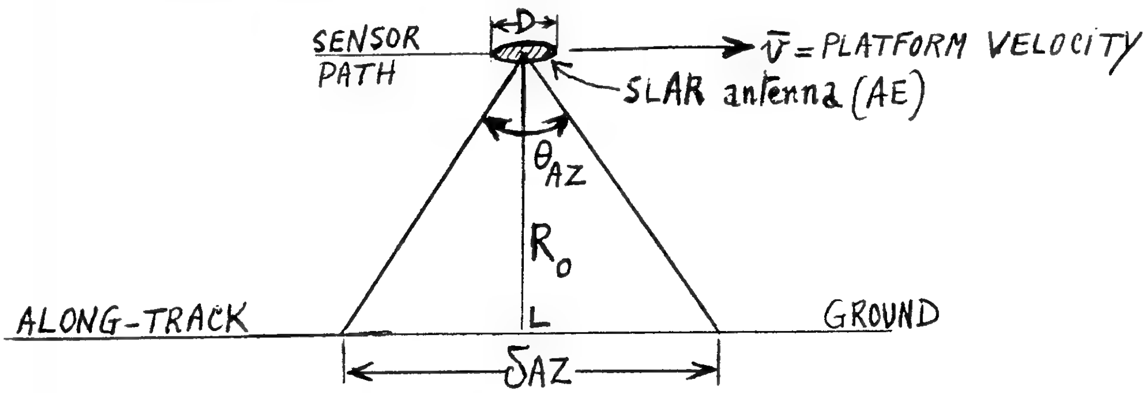


Fig. B8. <u>Derivation of the azimuth resolution on ground ; notice that δAZ is the footprint along track of the AE radiation pattern on ground</u>.

The real aperture length D is nothing else but the size of the real SLAR antenna along track (i.e., along the platform velocity). The corresponding real aperture (azimuth) beamwidth θ_{AZ} is then given by

$$\theta_{AZ} = \lambda/D$$

where λ is the wavelength of the SLAR.

Since θ_{AZ} is a small angle (a few degrees), δAZ is nothing else but the corresponding transverse size of the resolution cell and is given by

$$\boxed{\delta AZ = R_0\theta_{AZ} = R_0 \lambda/D}$$

The latter result is a dramatical one because the azimuth resolution δAZ
- increases with the range R_0
- is unfortunately proportional to the wavelength.

Unfortunately the wavelength of a radar sensor is much bigger than the wavelength of an EO sensor. Considering fig. B2, the ratio $\lambda_{radar}/\lambda_{EOsensor}$ is of the order 3 cm/3μ=10,000 making thereby the azimuth resolution 10,000 times worse for a radar sensor.

For instance, for a 10 m antenna (D=10m), operating (case of a spaceborne radar sensor) at 800 km range (R_0 = 800 km) at λ = 25 cm (P band), the formula of δAZ gives a minimum object size of 20 km, while this minimum object size would be of the order of 2 m for an EO sensor.

Conversely, the range resolution δR would be at least
- 150 m for a pulse width $T = 1\mu s$
- 3 km for a pulse width $T = 20\mu s$, because $\delta R > cT/2$

Clearly, a radar sensor necessitates a drastical reduction of both sizes δR and δAZ of the pixel on ground (the case being particularly dramatic for δAZ) in order to achieve images of the same quality as those given by the EO sensors.

The solution is quite obvious for the reduction of δR : it suffices to compress the pulse width to a value τ in the receiver as done by the PC (Pulse Compression) radar using a pulse compression ratio

$$\rho = T/\tau \approx B.T$$

which is nothing else but the well known time-bandwidth product. Values of $\rho = BT$ of the order of several thousands are quite feasible. Transmitting directly the much narrower pulse width τ (in order to bypass the range compression) is not feasible because it would require from the SAR a much higher peak power which would also increase the detectability by the enemy ELINT.

For δAZ the harmful effect comes from the large wavelength λ of all radar sensors. This very big value of λ could be compensated (in view of the formula $\delta AZ = R_0\lambda/D$) by replacing the real antenna of aperture length D by a very big linear array (see fig. B9) of aperture length L such that $L/D \approx 10{,}000$. Such a big linear array is evidently not feasible and totally unrealistic because such an array would be much bigger than the platform ! The solution will consist in replacing the very big linear array by a corresponding synthetic aperture with the same aperture length L as shown by fig. B9.

Assuming that the radar platform moves in a straight path, the synthetic aperture length L is (cfr fig. B10) nothing else but the path AB travelled by the radar platform during the dwell time (or integration time or illumination time)

$$T_S = t_{out} - t_{in} = L/V$$

where t_{in} is the instant where the target enters (point A) the real aperture beam and t_{out} is the instant where the target leaves (point B) the real aperture beam of beamwidth θ_{AZ}.

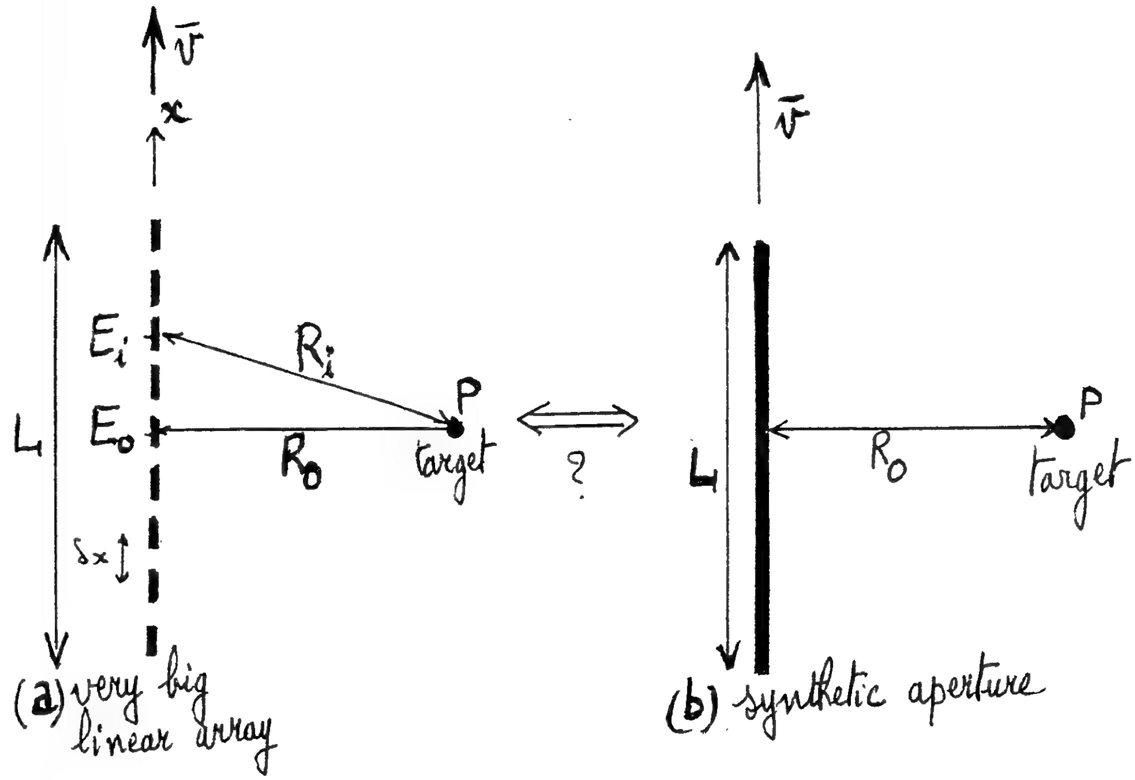


Fig. B9. Very big linear array and corresponding synthetic aperture of aperture length L

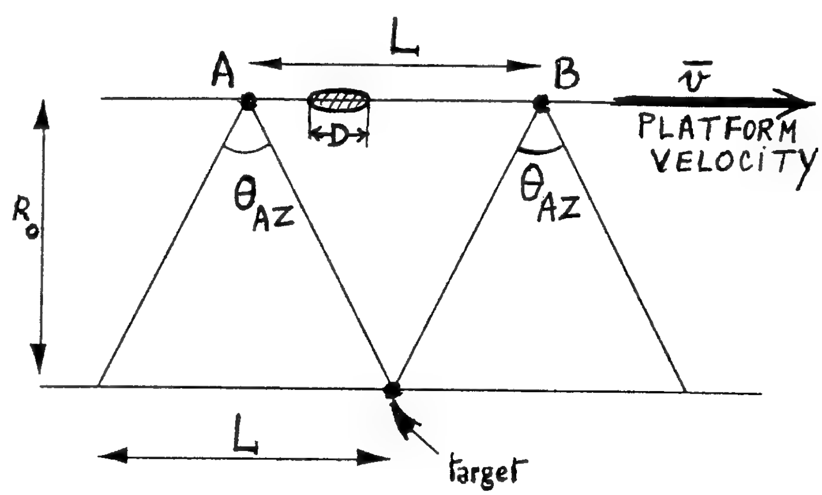


Fig. B10. Maximum synthetic aperture length L

Evidently, it is clear from fig. B10 that the (maximum) synthetic aperture length L depends on the real aperture beamwidth θ_{AZ}, which in turn depends on the real aperture length D because $\theta_{AZ} = \lambda/D$ and (since θ_{AZ} is a small angle)

$$\boxed{L = R_0\theta_{AZ} = R_0 \lambda/D}$$

If this synthetic aperture of length L can be synthesized, the corresponding synthetic beamwidth would be

resulting in a much smaller azimuth (along-track) resolution (i.e., smallest resolvable object along-track) given by

$$\delta AZ = R_0\theta_S = R_0\frac{\lambda}{L} = \frac{R_0\lambda}{R_0\lambda}.D = D$$

which is nothing else but the real aperture length along-track and is surprisingly range independent. The previous result has been obtained by a crude calculation. Accurate (exact) calculations show that the SAR performs even better and that the smallest resolvable object along-track (or azimuth resolution of the SAR) is given by

$$\boxed{\delta AZ = D/2}$$

the half of the real aperture length along track. Figures B11 and B12 summarize the previous results successively for a conventional SLAR (no SAR-like signal processing) and for a SAR, T being the transmitted pulse width and τ the compressed pulse width.

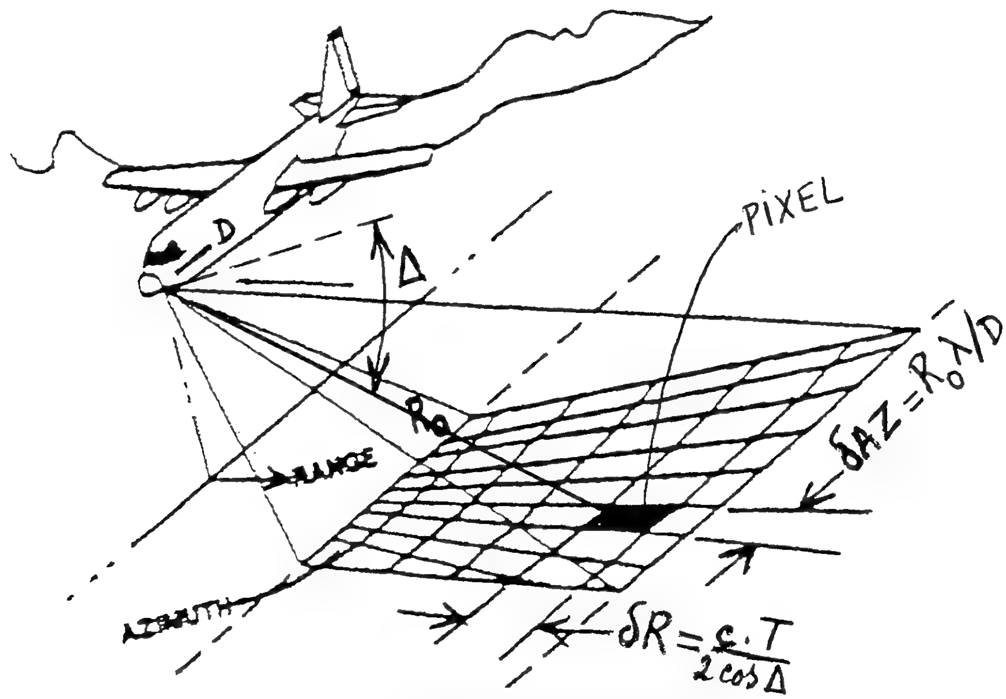


Fig. B11. Conventional SLAR pixel ; Δ is the depression angle

The SAR signal processing reducing the range resolution δR from $\frac{cT}{2\cos\Delta}$ to $\frac{c\tau}{2\cos\Delta}$ is termed **range compression** (which is exactly the pulse compression of a PC radar). The SAR signal processing reducing the azimuth resolution from $R_0\lambda/D$ to $D/2$ is termed **azimuth compression** ; the latter achievement is entirely due to the synthetic aperture which we shall discuss now in more details.

Notice that the platform straight path assumption is not a very crucial one and that target motion corrections (with respect to a straight path) are small.

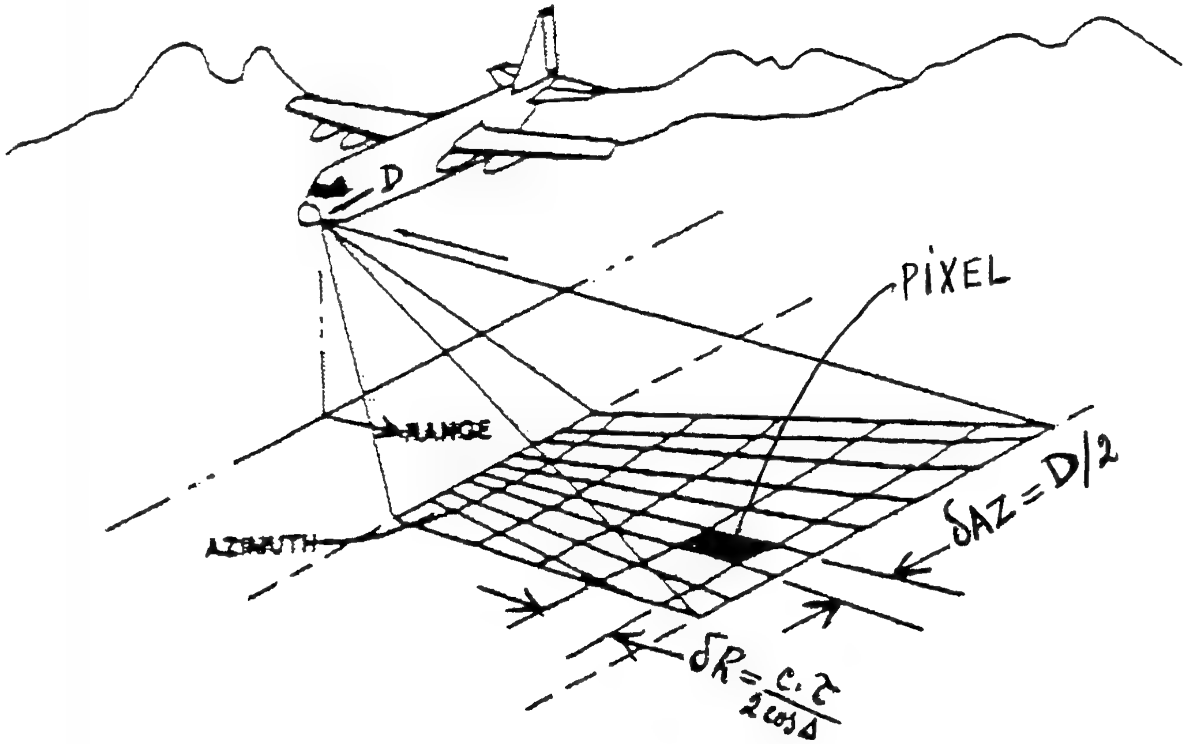


Fig. B12. SAR pixel

B. 2. The Synthetic Aperture

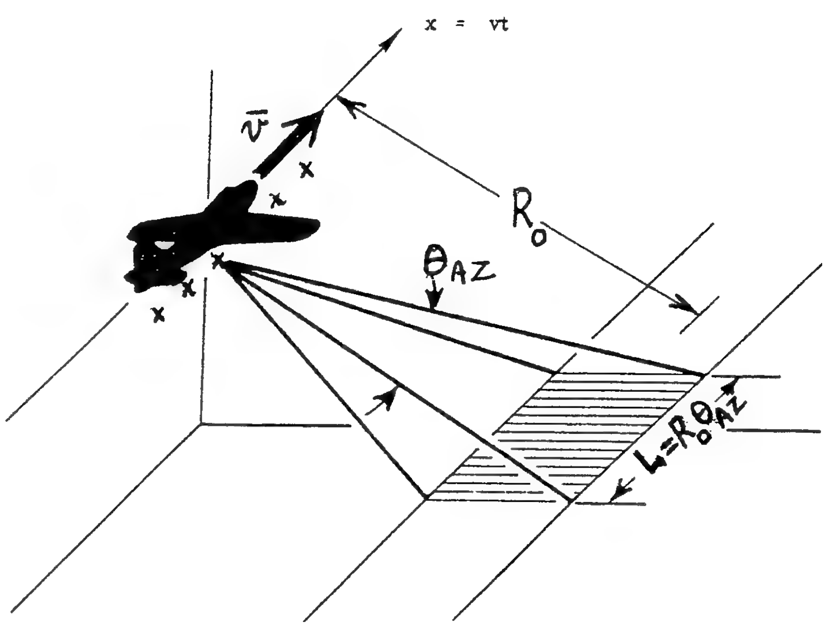


Fig. B13. Sidelooking radar configuration with the synthetic aperture length L

The principle of synthetic aperture processing is to realize the azimuth resolution appropriate to a large linear array (cfr fig. B9. a) by synthesizing the aperture of length L (see fig. B13) sequentially using just one radiating element (which is nothing else but the real SAR antenna of length D) moved along the whole synthetic aperture rather than instantaneously with all the signals available simultaneously in parallel. That means that the role of the various radiating elements E_i of the big linear array of fig. B9 (a) is played by the sequential positions (indicated by the crosses on fig. B13) of the single real SAR antenna at the successive instants of the transmitted pulses, provided the SAR records and stores both amplitudes and phases of the echoes at those sequential positions. This means that at each position indicated by the crosses on fig. B13, the single real antenna radiates a pulse, then receives and stores amplitude and phase of the reflected signal (called echo). These stored data are then processed in a manner analogous to the coherent weighted summation carried out in a large linear array. We remind that the focusing operation (it means the build up of the high directivity) of a large linear array represents a phase adjustment of the signal received on each radiating element E_i (of fig. B9. a) of the array so that, in the summation process, the contributions from all array elements E_i are combined in phase.

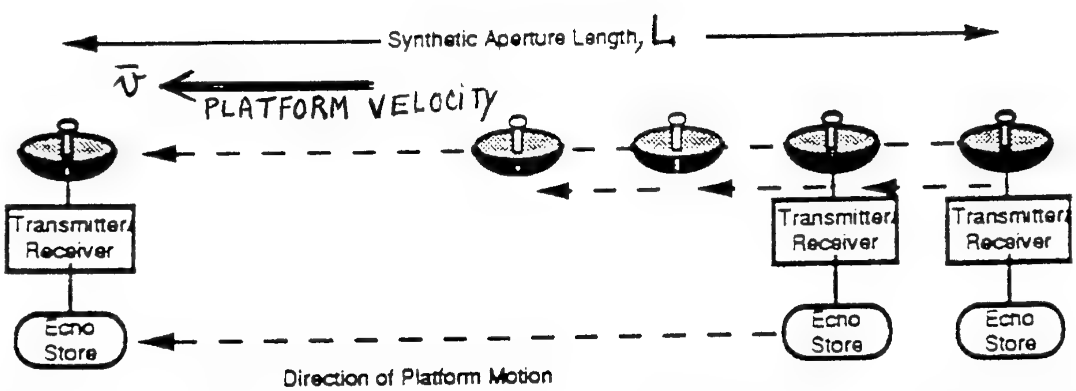


Fig. B14. The sequential positions (at the instants of the transmitted pulses) of the single real SAR antenna

Fig. B14 summarizes quite good the SAR principle :

- the larger the antenna (the larger the length L) the finer the details the radar can resolve
- in a SAR, one synthesizes a very long antenna (of length L) by combining the echoes received by the single real antenna as it moves along the targets.
- at each position of fig. 14 a pulse is transmitted, then return echoes pass through the receiver and are recorded (in amplitude and in phase) in an " echo store", for later processing into a SAR image.

Fig. B15 gives the (slant) ranges corresponding to the sequential positions of the single real antenna. At position E_i, the echo phase is proportional to $2R_i$ (because of the round trip).

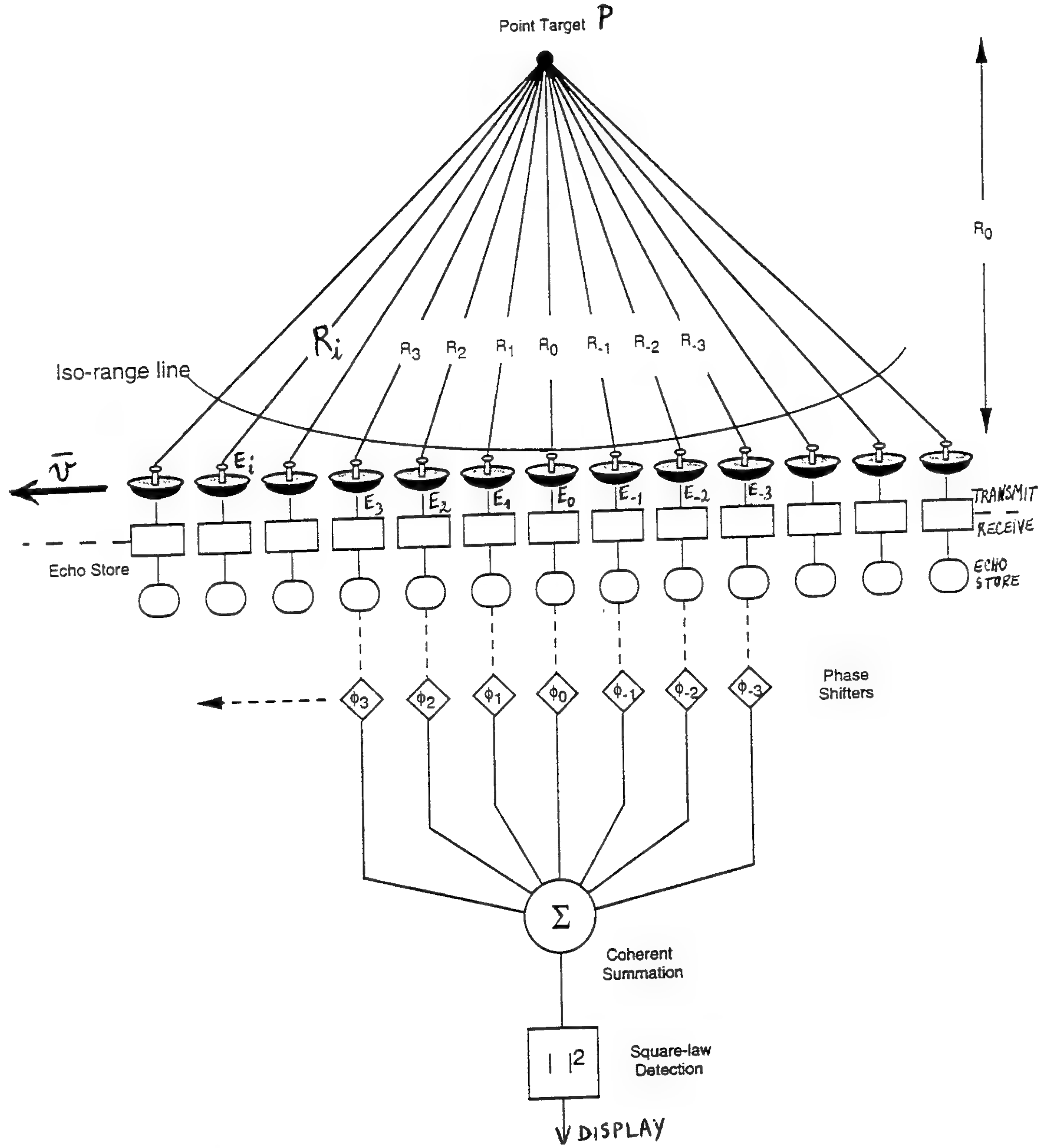


Fig. B15. Forming a SAR image of a point target by phase correction ; the iso-range line sketches in fact a diverging lens whose focal length is linked to R_0, the radius of curvature of the spherical diopter of this diverging lens

The principle of synthetic aperture is to combine the sequence of echoes (received at the sequential positions E_i of fig. B15) coherently - coherently means adding all echoes from the target P after compensating (i.e., matching) all phases - like a big linear array to get the effect of a large along-track antenna, and hence azimuth resolution.

The process of matching the phases of the echoes can be thought of as a frequency-domain matched filtering processing. In this respect it is very similar to matched filtering of a chirped pulse in a radar pulse compression (performed in the compression filter of a PC radar), and for this reason it is often referred to as azimuth compression, or azimuth correlation.

Let us summarize the SAR signal processing as follows :

1. The range compression (which is a pulse compression) is obtained by a matched filter, or, equivalently, by a correlation with a range reference signal which is a replica of the expected return from a point target at the same range.
2. Conversely, the azimuth compression is obtained by a correlation with an azimuth reference signal which is again a replica of the expected return from a point target at the same range.
3. Since (as we see later on) the azimuth reference signal is range dependent, range compression must be performed before azimuth compression.
4. Those 2 subsequent compressions are summarized, for a point target, by fig. B16 showing at each step the obtained improvement of the resolution materialized by the corresponding reduction of the pixel.

The final range resolution shown on fig. B16 corresponds to its minimum value $c\tau/2$ obtained for a depression angle Δ=0. Since, for a PC radar, the compressed pulse width τ is related to the radar bandwidth B by

$$B \approx \frac{1}{\tau}$$

the optimistic value of the final range resolution (i.e., the smallest resolvable object across track) is given by

$$\boxed{\delta R = \frac{c}{2B}}$$

We remind the amazing final azimuth resolution (i.e., the smallest resolvable object along track) as being

$$\boxed{\delta AZ = D/2}$$

where D is the aperture length along track of the real antenna.

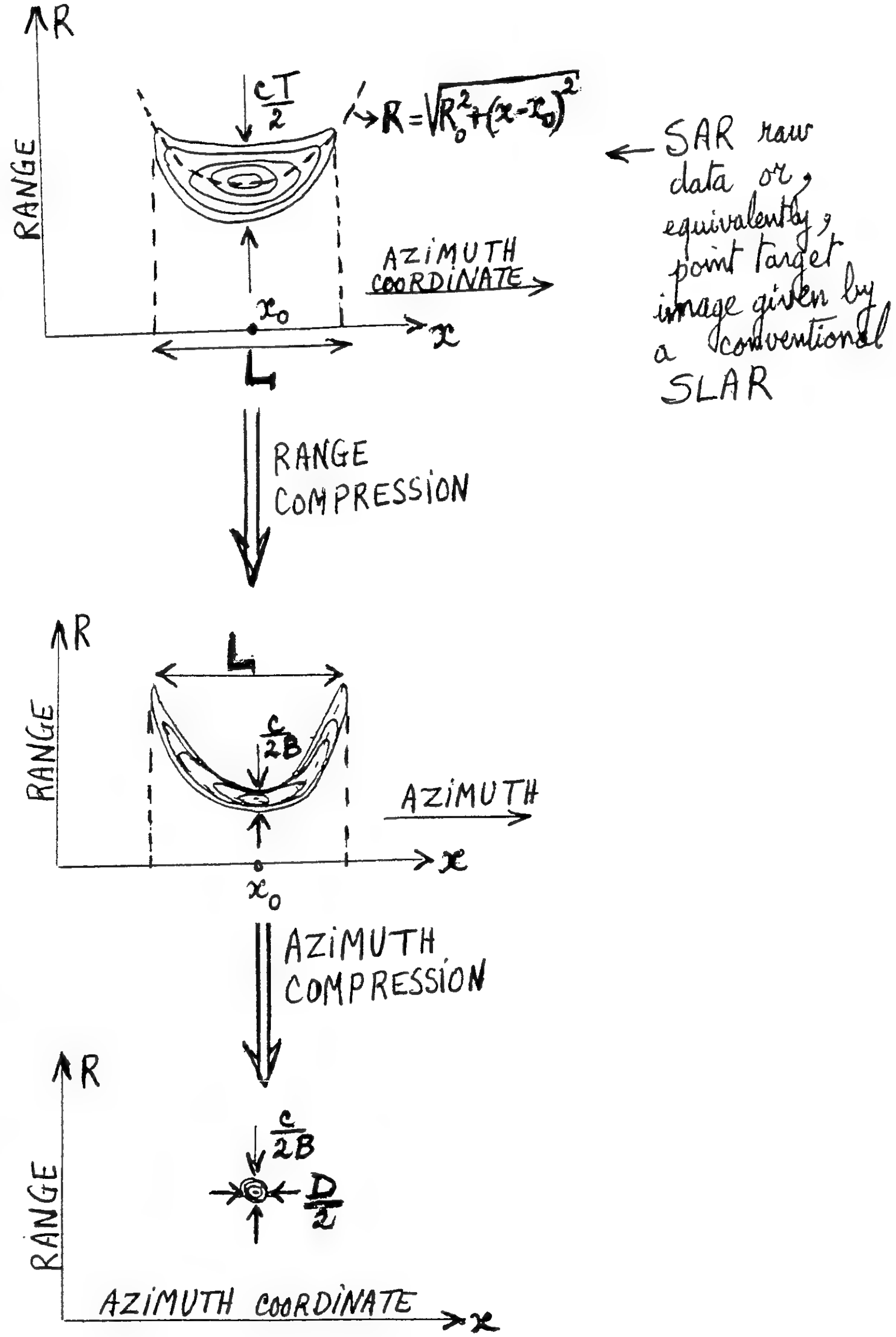


Fig. B16. The 2 successive compressions of a point target performed by the SAR signal processing. L is the synthetic aperture length but also the ground footprint along-track of the real antenna beam. The value c/2B of the range resolution corresponds to the optimistic case of a depression angle $\Delta= 0$

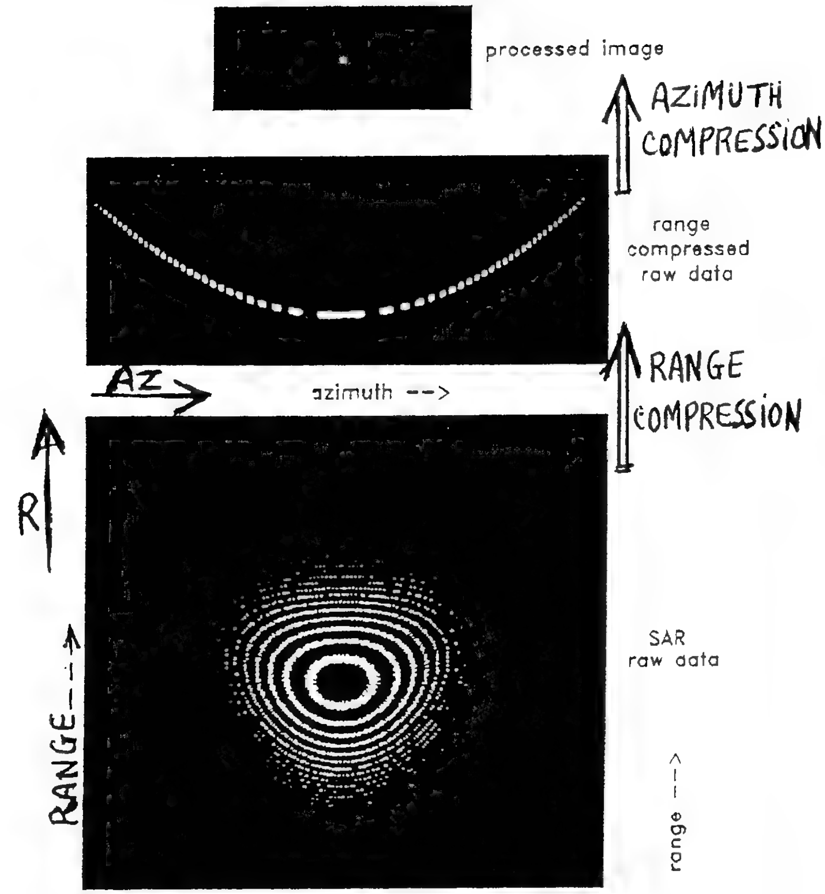


Fig. B17. The raw data received from a point target (lower image) show as well as the range compressed data the influence of range curvature

Fig. B17 illustrates the two successive compressions performed by a SAR on the raw data received from a real point target. The range curvature of fig.B17 is also called range migration and corresponds to the curve

$$R = \left[R_0^2 + (x - x_0)^2\right]^{1/2}$$

of fig. B16. The range migration curve described by the last formula gives the variation of the (slant) range of a particular point target when the radar platform moves along that target.

As we are going to see, the azimuth compression is based on the Doppler shift (or Doppler frequency) f_D due to the relative motion of the target with respect to the SAR and given by

$$\boxed{f_D = {2v_R}/{\lambda}}$$

where v_R is the radial component of the velocity of the target with respect to the SAR.

We remind that

- v_R and f_D are positive for a closing target
- v_R and f_D are negative for an opening target

B. 3. Basic Hardware Considerations

A simplified block diagram for a SAR is shown in fig. B18 assuming a digital signal processing ; indeed the previous optical processing has almost disappeared although it could come to a new life : electro-optical processing (using light valves) is again used by a US compagny performing almost real time processing ; nevertheless, presently, the vast majority of SAR's use digital processing for both range compression and azimuth compression.

The SAR is mounted on a platform moving at a constant velocity. The PRF must be sufficiently high to avoid azimuth ambiguities which are nothing else but velocity ambiguities. This criterion requires that the radar platform displacement cannot exceed one-half the real antenna size between successive transmit pulses;

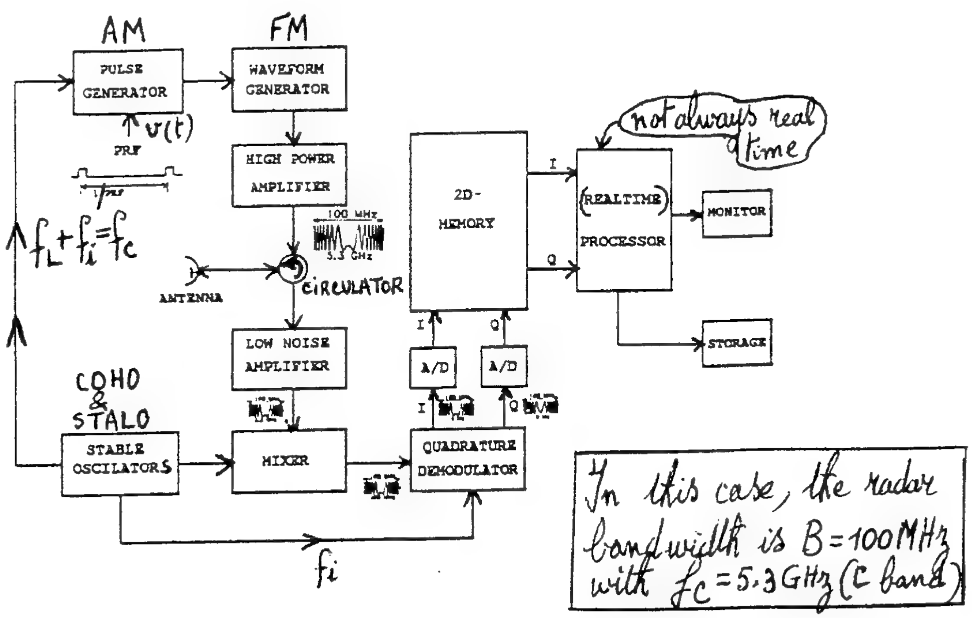


Fig. B18. Block diagram of a SAR (schematically)[W.KEYDEL]

in other words, if v is the magnitude of the SAR platform velocity,

$$v.T_R = v.IPP = \frac{v}{PRF} \le \frac{D}{2} \quad \text{or}$$

$$\boxed{PRF \ge 2v/D}$$

or

$$\boxed{PRF \ge \frac{v}{D/2}}$$

The latter condition is a constraint on the PRF which can easily be demonstrated as follows. It is very easy to show that the Doppler shifts f_D at the extremes (i.e., when the target enters or leaves the real antenna beam) are just $\pm v/D$.

So $f_{D\max} = v/D$

Since velocity ambiguities are avoided if

$$f_{D\,max} \leq \frac{PRF}{2}$$

this requires that

$$v/D \leq PRF/2$$

or $$PRF \geq 2v/D$$

Considering the block diagram of fig. B18, it should be stressed that

(a).In a SAR, phase stability is exceedling important. The prime oscillators which provide the signal (STALO and COHO) for the transmitter as well as the reference (COHO) for the receiver must be very stable. The timing of the transmit pulses must be very precise with respect to the prime oscillators ; in other words the PRF must be derived from the COHO (just as it is done in a PC radar to enable full cancellation of the fixed clutter) by dividing the COHO frequency f_i by an integer number N :

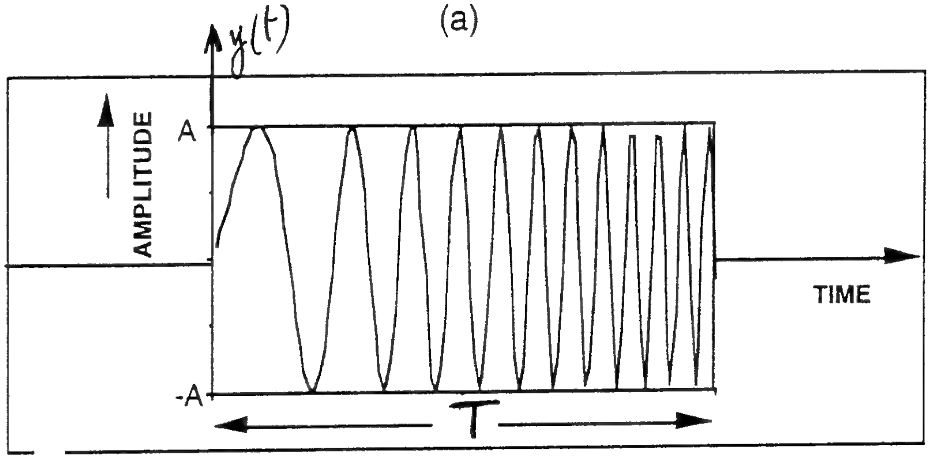
$$PRF = f_i/N$$

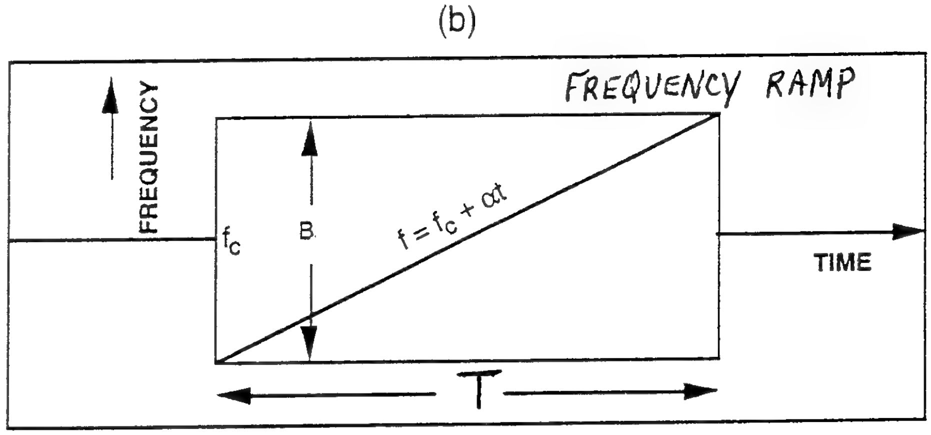
(b) Electronic circuits using a VCO (voltage controlled oscillator) can provide the desired (chirped) transmit pulse. Indeed, the transmit pulse must include a chirp signal in order to be able to perform pulse compression (which is nothing else but the range compression) in the receiver.

As suggested by the block diagram of fig. B18, the whole SAR signal processing is a digital one. Therefore, both range compression and azimuth compression must be performed in the baseband, i.e., on the bipolar video('s) I (and Q if necessary). That is a noticeable difference between the SAR and the PC radar : unlike the PC radar where the pulse compression is achieved within the IF stages, the SAR performs its pulse (i.e., range) compression in the baseband, i.e., on the bipolar video('s) I (and Q eventually).

The main reason for the baseband digital processing is that a digital processing requires an A/D (Analog to Digital) conversion and thus a sampling of the echo signal ; obviously this sampling is much easier (because of a lower sampling frequency) on the bipolar video(s) than on an IF (intermediate frequency) signal. Fig. B19 displays a typical (up) chirped transmit pulse with carrier frequency f_C and transmitted pulse width T. The corresponding echo signal could be down-converted directly to the baseband by a homodyne detection performed in a PSD (Phase Sensitive Detector) substracting f_C from the frequency ramp of fig. B19.

SAR THEORY





LINEAR FM OR 'CHIRP' WAVEFORM

$$(t) = A\,(t)\,\exp\left\{\underbrace{j2\pi\left[f_c t + \frac{1}{2}\alpha t^2\right]}_{\text{phase } \phi(t)}\right\}$$

α = slope of the frequency ramp

$$\text{FREQUENCY, } f = \frac{1}{2\pi}\frac{d\phi(t)}{dt} = f_c + \alpha t$$

TRANSMIT PULSE LENGTH = T

Fig. B19. LINEAR FM OR "CHIRP" WAVEFORM

But usually the down-conversion to the baseband is done from the IF echo signal (IF = intermediate frequency) in a PSD (or two PSD's in case both bipolar video's I and Q are needed) which will substract the IF frequency

$$f_i = (f_1 + f_2)/2$$

from the IF frequency ramp. In the previous formula, f_1 and f_2 are the extreme frequencies of the IF frequency ramp ; those frequencies are simply related to the radar bandwidth B and the compressed pulse width by

$$B = f_2 - f_1 = 1/\tau$$

Fig. B20 sketches the whole process of down-conversion from the IF signal to the baseband frequency f_{BB} history, the corresponding baseband phase

$$\phi_{BB} = \int_0^t f_{BB}(t)\,dt$$

and finally the baseband signal $\cos\phi_{BB}$ which is nothing else but the echo bipolar video corresponding to the chirped transmitted pulse of fig. B19.

The baseband signal $\cos\phi_{BB}$ of fig. B20 will be also the range reference function (displayed by fig. B21) for the correlation operation needed to achieve the baseband pulse compression, i.e., the range compression as a part of the SAR signal processing.

A correlation needs always a reference function. In the case of any radar, the <u>appropriate reference function</u> is a replica of the expected return from a point target at the same range.

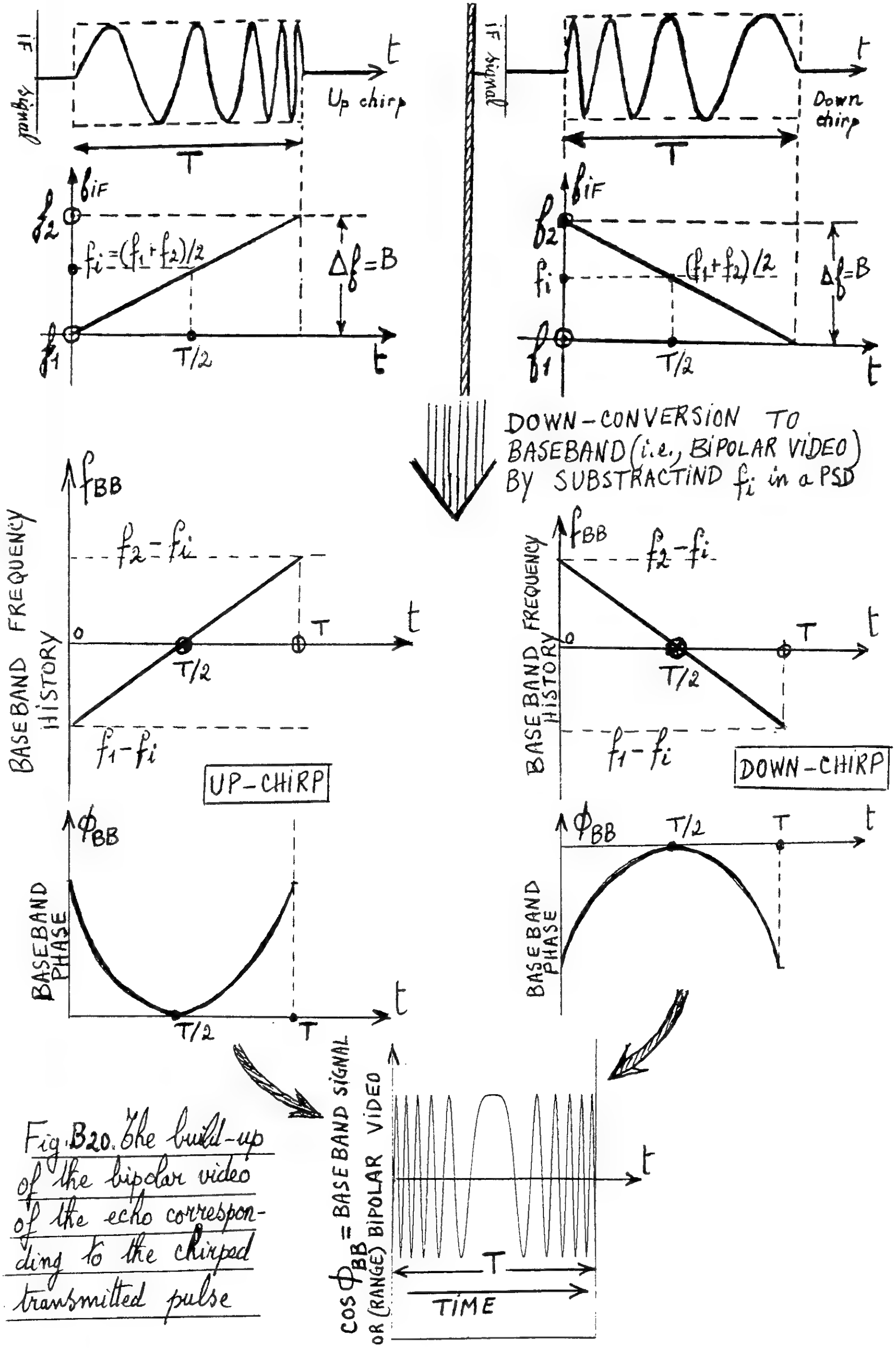


Fig. B20. The build-up of the bipolar video of the echo corresponding to the chirped transmitted pulse

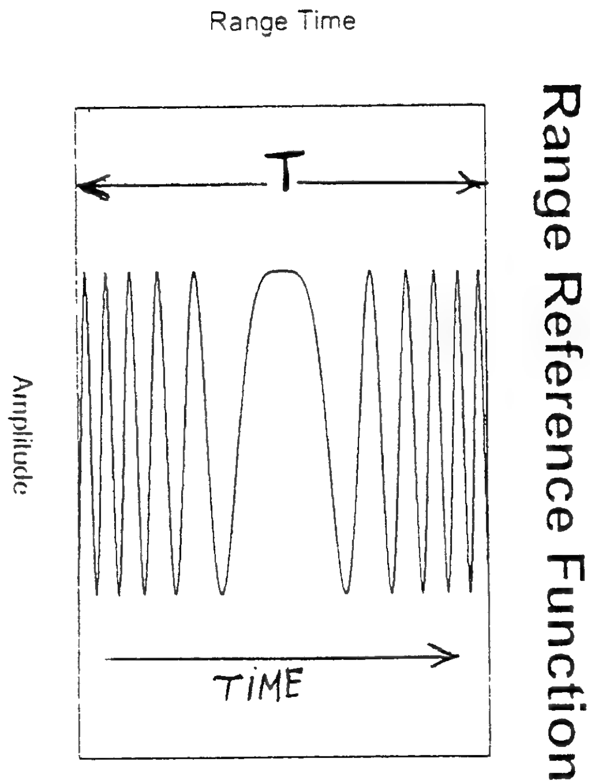


Fig. B21. The range reference function or range reference signal whose complex conjugate of the Fourier transform is the transfer function of the matched filter needed for pulse (i.e., range) compression

B. 4. The Doppler History and the Azimuth Reference Functions for Azimuth Compression

4. a. The straightforward but difficult way for the derivation of the Doppler history

We consider the case of a point target. Fig. B22 displays again the coordinate system with the coordinate along-track x corresponding to the azimuth dimension of the radar images. The origin of x as well as the origin of the time t are chosen when $R = R_0$, i.e., when the point target is purely broadside, or, equivalently, at the closest approach range R_0. In other words, the origins of x and t correspond to the point of closest approach ($R = R_0$), so we can write

$$R^2 = R_0^2 + x^2 \qquad \text{and } x = vt$$

hence

$$R = \left(R_0^2 + x^2\right)^{1/2} = R_0\left[1 + \frac{x^2}{R_0^2}\right]^{1/2}$$

This can be expanded

$$R = R_0\left[1 + \frac{1}{2}\frac{x^2}{R_0^2} - \frac{1}{8}\frac{x^4}{R_0^4} + ...\right]$$

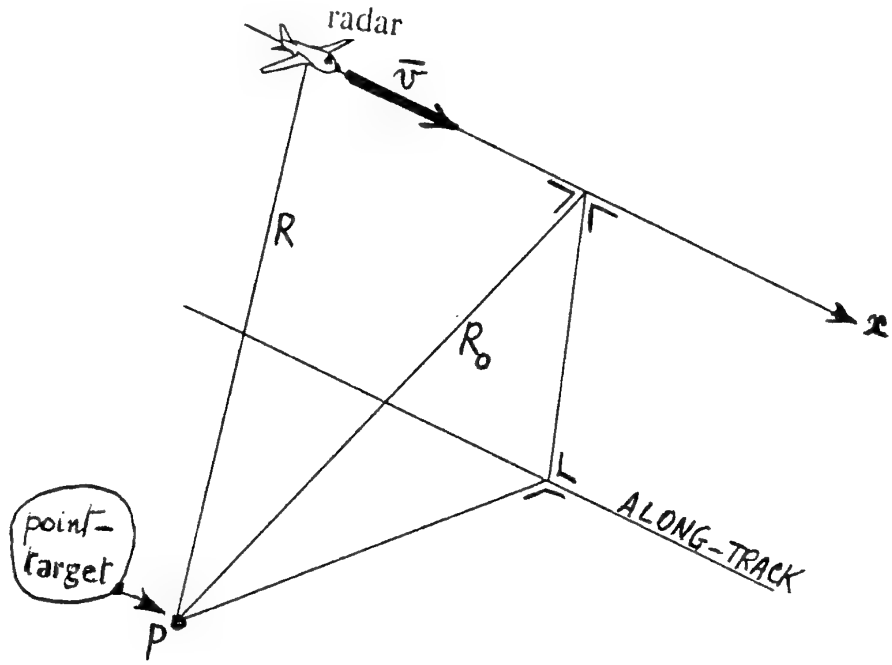


Fig. B22. SAR co-ordinate system for a point-target

If we limit this series expansion to the first two terms :

$$R = R_0 + \frac{x^2}{2R_0}$$

The two-way (because of the round trip of the radar wave) phase of the sequence of echoes (we remind that those echoes are received at a rate given by the PRF of the radar) is then given (2 R because of the round trip) by :

$$\phi(x) = -2R.\frac{2\pi}{\lambda}$$

the negative sign occuring because an increasing path length represents a phase lag. So

$$\phi(x) = -\left[\frac{2R_0}{\lambda}.2\pi + \frac{2x^2}{2R_0\lambda}.2\pi\right]$$

or
$$\phi(x) = \phi_0 - \frac{2\pi x^2}{R_0\lambda}$$

with ϕ_0 being $\left[-\frac{2R_0}{\lambda}.2\pi\right]$, i.e., the phase at closest approach.

We see that the phase is a quadratic (or parabolic) function of x displayed by fig. B23 which is formerly identical with the base-band phase ϕ_{BB} of a down-chirp on fig. B20, provided we take into account that

$$x = vt$$

where v is the magnitude of the platform velocity. The previous calculation is obviously valid for a point-target only.

Fig. B23 displays also the extremes of the along-track footprint of the beam of the real radar antenna ; since (see fig. B8) this along-track footprint is $R_0\lambda/D$, those extremes are $\pm\frac{1}{2}\frac{R_0\lambda}{D}$.

Since x = vt, we can also consider the phase variation of fig. B23 as a function of time, to give the Doppler frequency f_D (due to the relative motion of the target with respect to the radar).

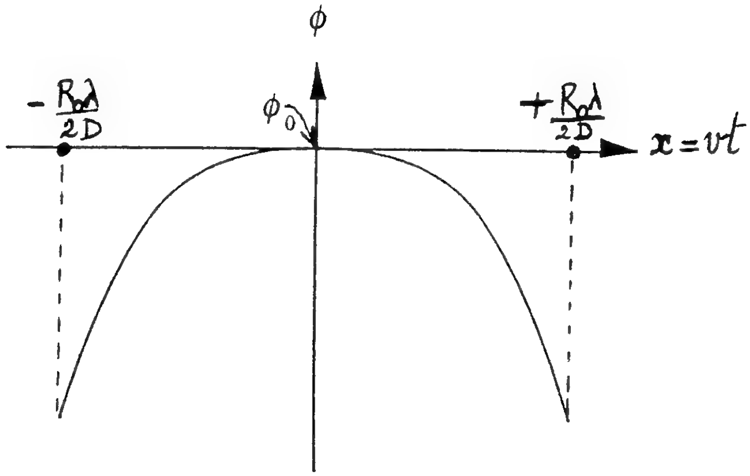


Fig. B23. Echo phase as a function of x=vt

So $$\phi(t) = \phi_0 - \frac{2\pi v^2 t^2}{R_0 \lambda}$$

Thus the Doppler frequency history is expressed by

$$\boxed{f_D = \frac{1}{2\pi}\frac{d\phi}{dt} = -\frac{2v^2 t}{R_0\lambda} = \frac{-2v}{R_0\lambda}x}$$

So this quadratic variation of phase represents a linearly-variying Doppler frequency displayed by fig. B24 which is formerly identical to the baseband frequency history of a down-chirp on fig. B20. Again, fig. B24 displays the extremes $\pm\frac{R_0\lambda}{2D}$ of the footprint of the beam of the real antenna on ground, where D is the along-track dimension of the real antenna (the real aperture) ; the corresponding limits (as we announced when the constraint PRF $\geq 2v/D$ was computed) of the Doppler frequency are $\pm v/D$.

The expression

$$\boxed{f_D = -\frac{2v^2 t}{R_0\lambda}}$$

and the corresponding fig. B24 are those of a down-chirp baseband frequency, thus a negative frequency ramp whose slope $\left[-\frac{2v^2}{R_0\lambda}\right]$ is clearly range (the range R_0 at closest approach) dependent. The corresponding baseband signal (i.e., the corresponding bipolar video)

$\cos\phi = \cos\left[\int_0^t f_D(t)dt\right]$ is then represented by fig. B25 for various values of the range R_0 at closest approach. Obviously the azimuth reference functions of fig. B25 depend not only on the range R_0 but also on the platform velocity v.

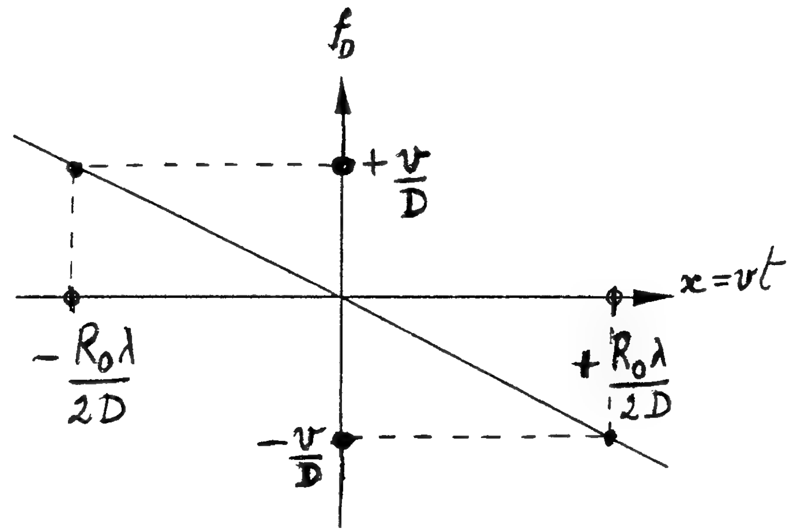


Fig. B24. Doppler frequency as a function of $x = vt$

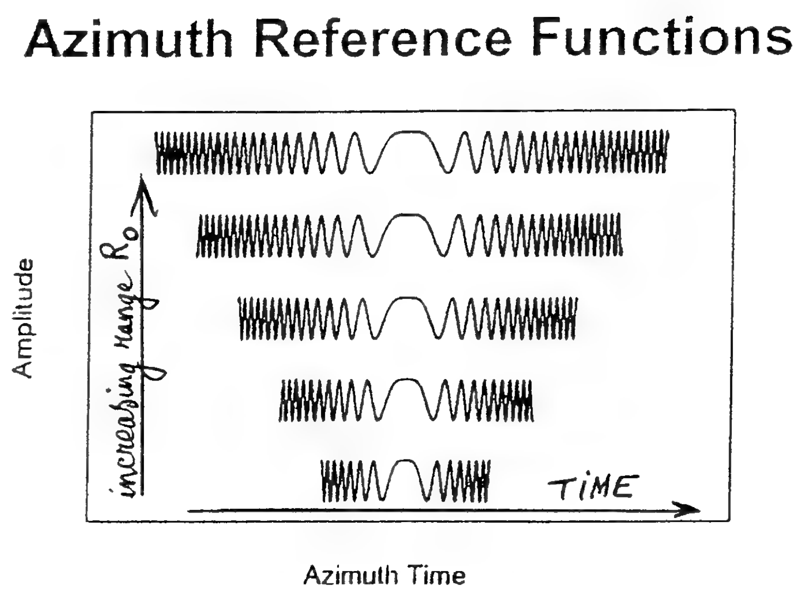


Fig. B25. The azimuth reference functions (replica of the expected returns from a point target at the same ranges)

The curves of fig. B25 represent the azimuth reference functions for the correlation operation needed to achieve the baseband azimuth compression which, after the range compression, will consitute the second part of the SAR signal processing. The curves of fig. B25 are similar to the range reference function of fig. B21.

The azimuth reference functions of fig. B25 are not the true azimuth bipolar video's (for different ranges R_0) because the azimuth bipolar video is not obtained instantaneously ; on the contrary this bipolar video is acquired after numerous pulses have been transmitted, the number of those transmitted pulses being (if T_R represents the IPP) : $\frac{T_S}{T_R} = \frac{L}{v}.PRF = \frac{\lambda R_0}{D}.\frac{PRF}{v}$

In order to retrieve the azimuth bipolar video, the successive echoes (from the successive transmitted pulses) have to be stored in amplitude and phase.

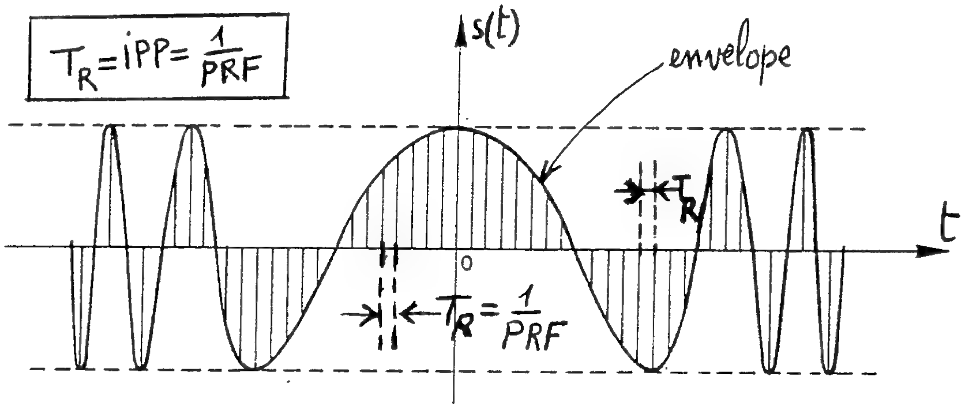


Fig. B26. True bipolar video of a point-target along track at a given R_0

As shown by fig. B26, the true azimuth bipolar video (i.e., the bipolar video along-track) of a point-target is composed of equidistant pulses separed by a time interval $T_R = \frac{1}{PRF}$; those pulses have an envelope given by the azimuth reference function of fig. B25 corresponding to the considered range R_0.

The vertical stripes of fig. B26 are the echo pulses emanating from the same point target and originated from the successive transmitted pulses (i.e., the successive pulses transmitted by the radar).

In essence, the SAR azimuth bipolar video of fig. B26 is similar to the bipolar video's I and Q of fig. B27 except that the Doppler frequency (which is the frequency of the envelope) is linearly varying with time in the case of the SAR.

Notice that the azimuth bipolar video represented by fig. B26 does not encompass the influence of the true antenna radiation pattern. The upper curve of fig. B28 represents the envelope of the true azimuth bipolar video taking into account the radiation pattern of the true antenna. The

lower curves of fig. B28 express the fantastic effect of the azimuth compression.

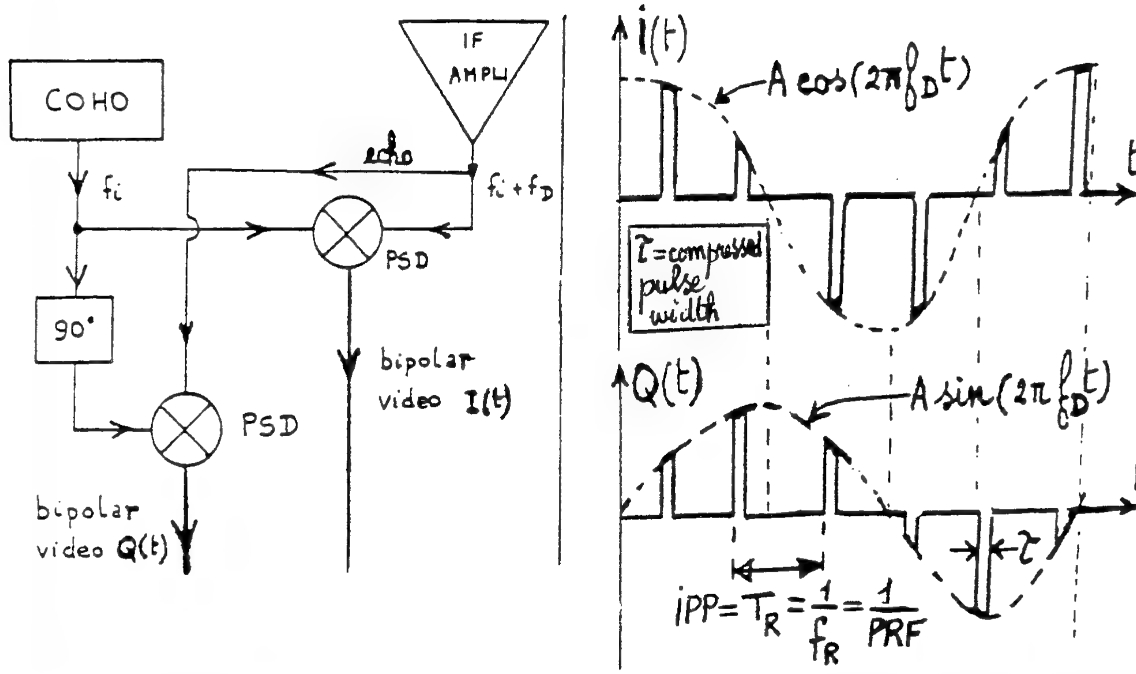


Fig. B27. The bipolar video's I and Q from a mobile target flying at constant velocity, in the base-band of a coherent radar (either a MTI radar or a pulse Doppler radar)

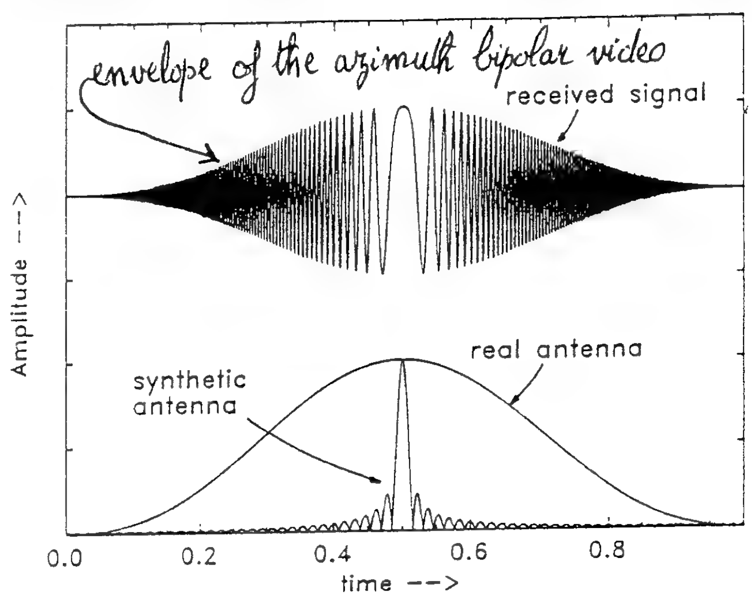


FIG. B28. Amplitude of a pulse response (upper curve) from a point target and SAR-prozessed impuls response of a point target (lower curve) following in comparison with point target response for a real aperture radar.

4. b. The easy way to establish the Doppler history along track for a point target

Since the SAR platform is flying along the point target P, conversely it can be considered that the SAR is stationary and that the point target P is moving in a straight path with a velocity $\bar{v}$ in the opposite direction : see fig. B29 where $PP_0 = x = vt$, P_0 being the target position at closest approach. Since fig. B29 represents the case of an opening target, the radial velocity v_R is negative and is thus given by $v_R = -v \sin\varepsilon$. But ε is a small angle and thus $\sin\varepsilon \approx tg\varepsilon = {PP_0}/{R_0}$

Hence $v_R = -v.{PP_0}/{R_0} = -{v.x}/{R_0} = -{v^2 t}/{R_0}$

and the corresponding Doppler frequency

$$\boxed{f_D = {2v_R}/{\lambda} = -\frac{2v^2 t}{\lambda R_0}}$$

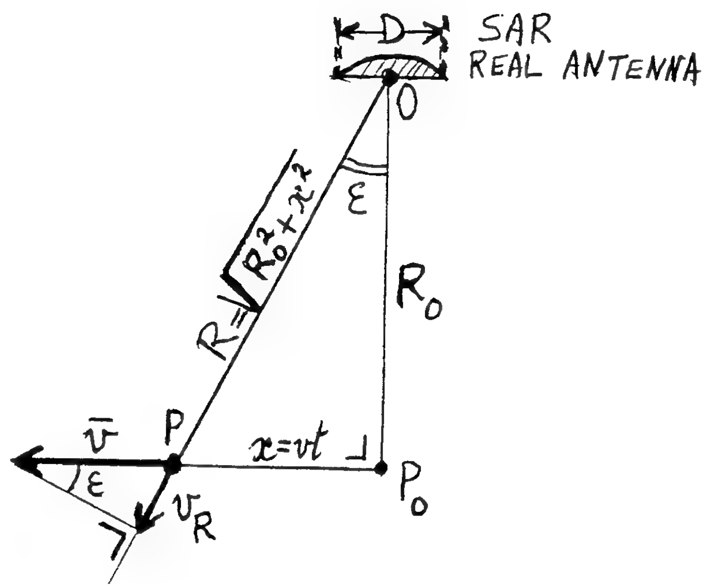


Fig. B29. Relative motion of the point target ; case of an opening target.

which is exactly the same as the Doppler shift f_D we have previously found through a hard and tedious way. From this point, it suffices to restart the whole reasoning following fig. B24 and the corresponding formula of the Doppler frequency f_D, knowing that the corresponding phase is given by

$$\phi = \int_0^t f_D(t).dt$$

and that $\cos\phi$ is the envelope of the azimuth bipolar video.

Since we have used a point target to establish the azimuth reference functions (given by $\cos\phi$), those azimuth reference functions are responses so that their complex conjugated Fourier

Transforms are the transfer functions of the matched filters which could be used alternatively to perform azimuth compression.

Fig. B30 displays the baseband echoes (as a function of time) corresponding to successive transmitted pulses. Out of those time varying echoes, how can we retrieve, for a particular point-target at a given range R_0, the successive (alternatively positive and negative) pulses forming the azimuth bipolar video of fig. B26, the envelope of this bipolar video being the azimuth reference function of fig. B25 corresponding to the given range R_0 ?

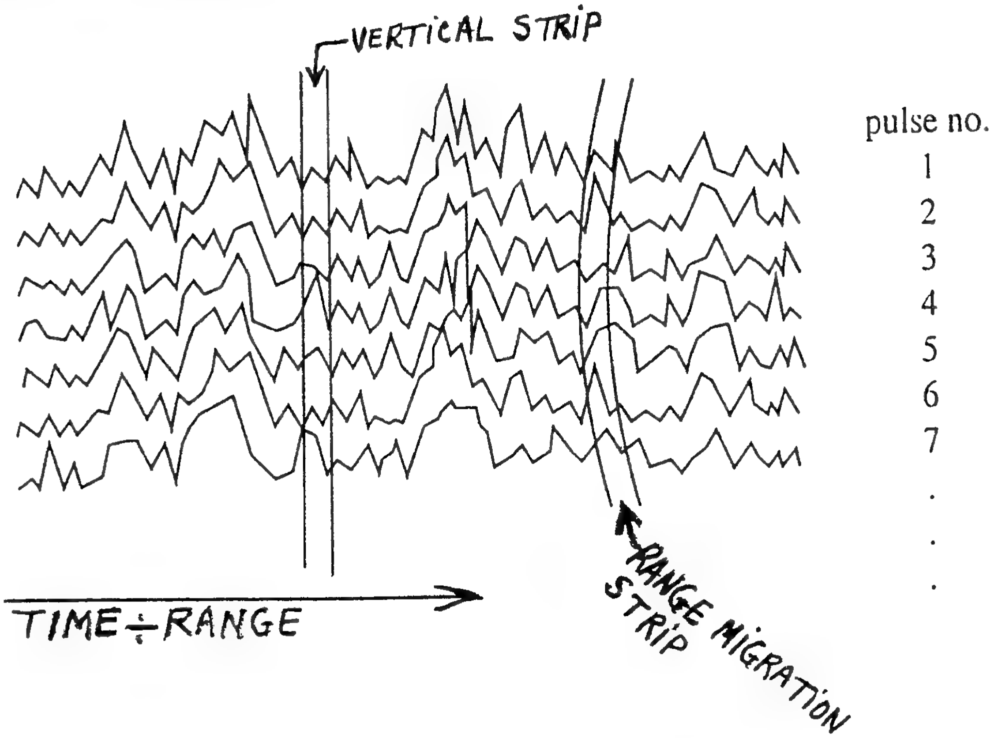


Fig. B30. Basis of SAR processing

Since the elapsed time is proportional to range in a pulse radar, those pulses forming the azimuth bipolar video should be found in the vertical strip of fig. B30. But because of the range migration (meaning that the range of each point target varies with time $t = x/v$) described by (see fig. B29)

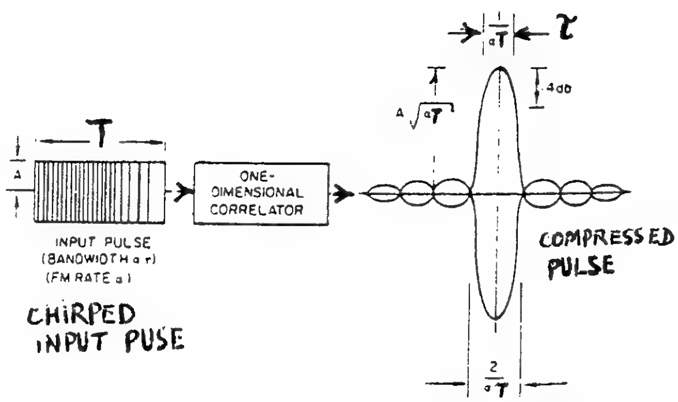
$$R = \left[R_0^2 + x^2\right]^{1/2}$$

those echo pulses belonging to the same point-target have to be retrieved from the range migration strip of fig. B30.

Each imaged cell is known as pixel. Each pixel corresponds to a particular target at a given range R_0. To obtain the final video signal (going to the screen displaying the final high resolution image) corresponding to one pixel, the echoes at constant range R_0 from each curve of fig. B30 are taken, each echo is phase weighted (this phase weighting is performed by the correlations described in next paragraph) and the weighted echoes are summed. This process is repeated at all ranges and all azimuths and constitutes the sophisticated SAR signal processing.

B. 5. The Final Digital SAR Signal Processing.

Both range compression and azimuth compression are in fact pulse compressions. As known from the theory of the explanation of a PC (Pulse Compression) radar, each compression can be realized by the corresponding matched filter or, equivalently, by a correlation with the appropriated reference functions (those reference functions being replica of the expected returns from a point target at the same range). Fig. B31 represents the full digital SAR processing.



One-Dimensional Correlator (⊗)

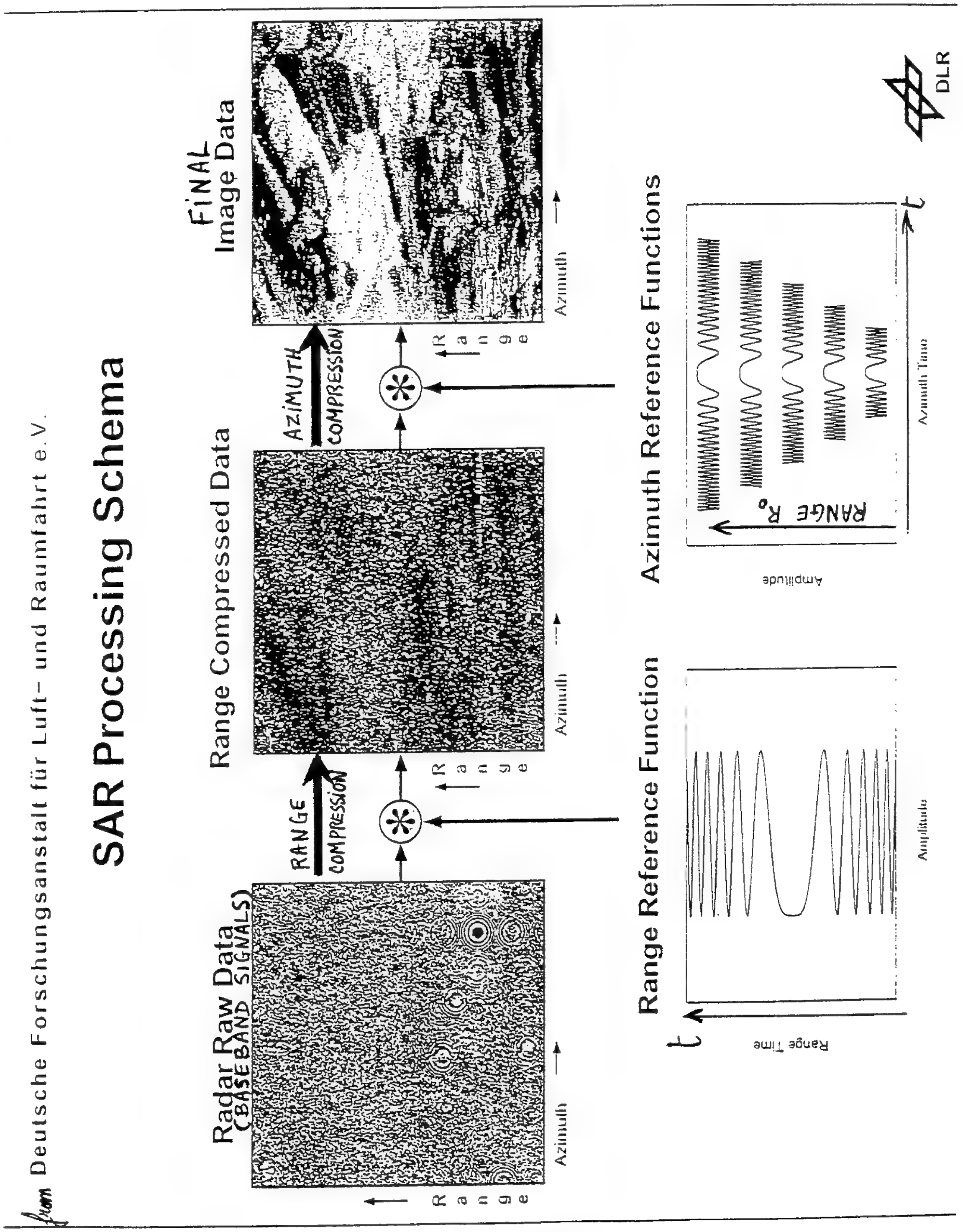


Fig. B31. SAR Processing Schema

As suggested by fig. B31 (this figure shows only baseband signals)

- the range compression is obtained by a correlation performed on each vertical strip of the radar raw data (so, after each transmitted pulse)
- the azimuth compression is obtained by a correlation performed on each horizontal strip (in fact, more accurately, on each range migration strip) of the range compressed data, i.e., after numerous transmitted pulses.

Since the azimuth reference functions are range dependent (they are depending on the range R_0 at closest approach), the range compression must be performed before the azimuth compression may be started. Those two subsequent operations are nicely summarized by fig. B32. The 1-D line of fig. B32 corresponds chiefly to the range migration which expresses that the range of a point target varies with $x = vt$.

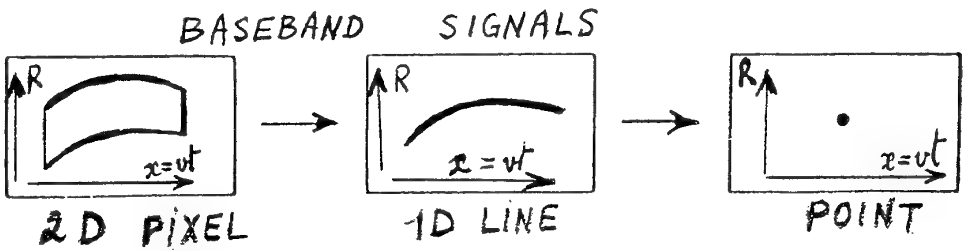


Fig. B32. Range processing followed by azimuth processing achieving an intrinsic 2-D (range and azimuth) data processing (the 1-D line corresponds to the range migration)

The intrinsic 2-D processing performed in 2 subsequent steps on fig. B32 can sometimes be done in one single step as illustrated by fig. B33 (depending on the algorithm approach)

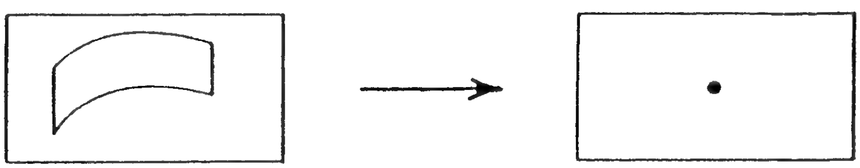


Fig. B33. 2-D processing : simultaneous range and azimuth data processing.

Notice : on fig. B31, the azimuth reference function has to be changed when the range R_0 (at closest approach) changes approximately by $2D^2/\lambda$ where D is the real aperture length along track. Notice also that the azimuth compression depends also on the SAR platform velocity because the magnitude v of this velocity clearly appears in the expression of the azimuth reference functions.

B. 6. SAR Imaging of Moving Targets

Up till now we implicitely considered only stationary targets (i.e., targets stationary with respect of the ground scene to be imaged). Considering the azimuth Doppler history (i.e., the sequence of echoes along track from the same stationary target) of fig. B24 , we remind that fig. B24 (as well as fig. B34) illustrates the relation (valid for a stationary target)

$$\boxed{f_D = -\frac{2v}{R_0\lambda}x}$$

which is a linearly varying Doppler history with a slope $\left(-\frac{2v}{R_0\lambda}\right)$. The last relation expressing this linear frequency ramp f_D as well as fig.B24 remind us that the exact position along track of the stationary target is given by x=0 (which corresponds to the range R_0 at closest approach , i.e., when the target is purely brodside), i.e., by the x value of the zero crossing point of the Doppler history of figures B24 and B34. Considering now a stationary target and a moving target at the same location (i.e., with the same x=0 coordinate along track). Their respective azimuth Doppler histories as a function of the x-coordinate along track are both given by fig. B34 showing that, with respect to the stationary target, the moving target (at the same location) exhibits a Doppler offset expressed by

$$\boxed{\text{Doppler offset} = {}^{2v_R}\!/_{\lambda} = {}^{2v_R f_c}\!/_{c}}$$

where v_r is the radial component of the velocity of the moving target with respect to ground and f_c is the radar carrier frequency.

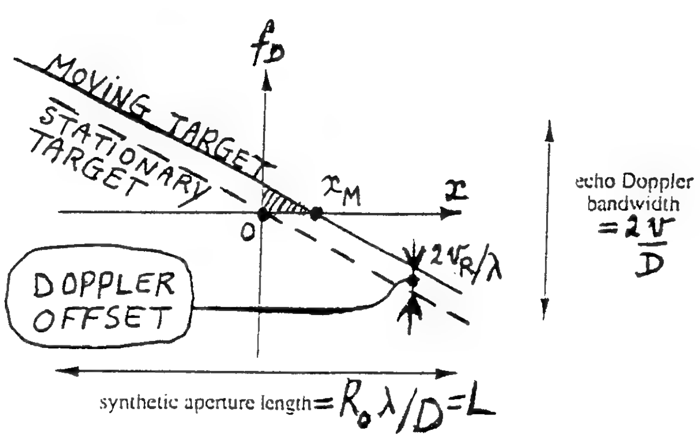


Fig. B34. A target with a radial velocity is matched filtered by the SAR processing with an azimuth shift (or azimuth displacement) x_M

Since the x-coordinate along track of the target is given by the zero crossing point of the Doppler history, it follows (see fig.B34) that the SAR processing will consider that the x-coordinate along track of the moving target is given by the azimuth shift (or azimuth offset) x_M instead of the true value x=0. This azimuth shift (or azimuth displacement)x_M satisfies (considering the hatched triangle) :

$$\frac{x_M}{\text{Doppler offset}} = \frac{L}{2v/D} = \frac{R_0\lambda/D}{2v/D} = \frac{R_0\lambda}{2v} \quad \text{(= inverse of slope)}$$

$$\text{Or } \frac{x_M}{2v_R/\lambda} = \frac{R_0\lambda}{2v}$$

Hence

$$\boxed{x_M = v_R R_0/v}$$

where

- v_R is the radial component of the velocity of the moving target with respect to the ground
- v is the SAR platform velocity with respect to the ground
- R_0 is the range at closest approach

Consequently, the SAR processing will result in a displacement x_M along track of the moving target with respect to its true location. This is nicely illustrated by figures B35 and B36.

Fig. B35 shows an image from an airborne SAR of a moving train. Because the train has a component of velocity in the range direction (i.e., in the radial direction) , the train image is shifted (i.e., displaced) with respect to the stationary railway track; so the train appears to be travelling not along the railway track, but displaced to the side. From the formula

$$\boxed{x_M = v_R R_0/v}$$

it follows that it is possible to estimate the target radial velocity v_R , if one knows the platform velocity v, the geometry R_0 and the azimuth shift (to know x_M, it is necessary to know the true position of the target).

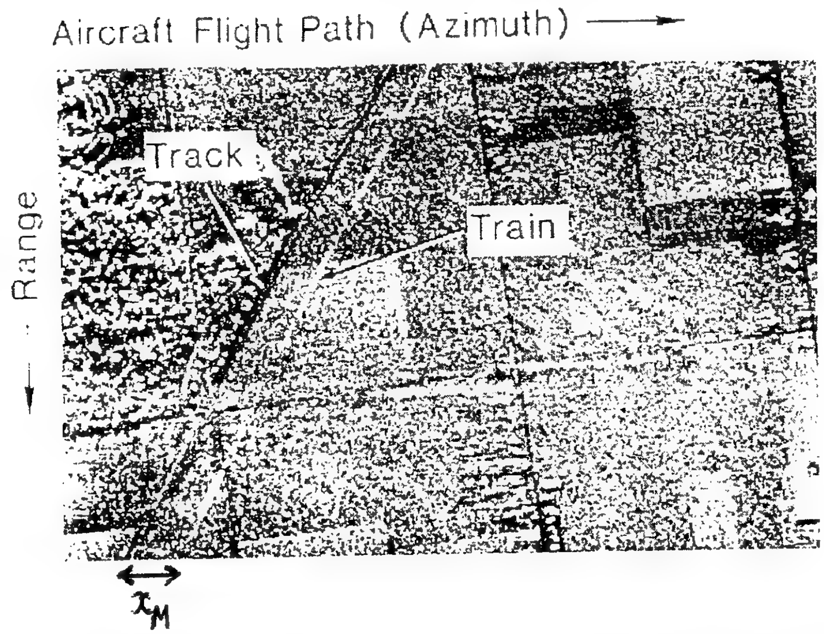


Fig. B35. SAR image of a moving train (after Rufenach et al.)

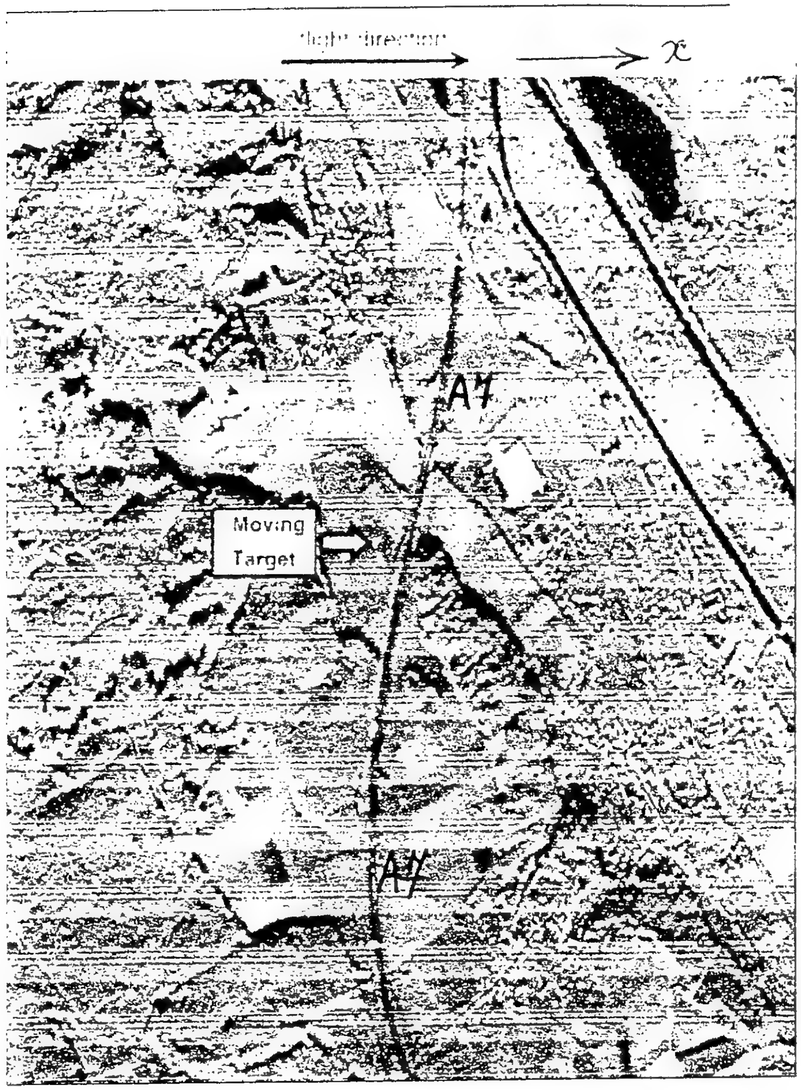


Fig. B36. C-band image of the high resolution real time processor.The imaged area shows the Iller river in the vicinity of Altenstadt, Bavaria, Germany.

Fig. B36 shows a real-time image from DLR airborne SAR during a test flight in the vicinity of Oberpfaffenhofen (location of DLR) The main SAR parameters were: aircraft altitude ca.3000m, ground speed ca.80 m/s and C-band. The image dimensions are approximately 3000m$\times$3000m.On fig. B36, the indicated moving target is a car displaced off the highway A7. This displacement occurs due to the Doppler frequency offset $2v_R/\lambda$ introduced by the motion of the car with respect to the highway A7. It is worth to give here **the relevant parameters of the SAR's carried by the European Space Agency's ERS-1 and ERS-2:**

carrier frequency: 5.3 GHz
pulse bandwidth (f2-f1$\approx 1/\tau$): 15.5MHz
pulse width T: 37.1us
peak transmitter power: 4.8kw
swath width: 80km
PRF: 1.64kHz < PRF < 1.72kHz
pixel size: 30m$\times$30m

B. 7. MTI (Moving Target Indication)

In many situations, it is useful to be able to distinguish moving targets from stationary ones. In previous paragraph, we already saw that the image of a target with a component of velocity in the range (i.e., the radial) direction will suffer an azimuth shift x_M(i.e., an off displacement along track), but unless the true position is known, this does not allow the detection of moving targets, i.e. moving target indications (MTI).

There are essentially two ways to perform MTI with a SAR :

- the 1st way is DPCA (Displaced Phase Center Array) processing.
- the 2d way is STAP (Space-Time Adaptative Processing)

a. <u>STAP</u>

By using an along-track array, it is possible to perform both spatial-domain (directional) filtering and time-domain (Doppler) filtering. This is known as STAP (Space-Time Adaptative Processing) and is the subject of considerable current research.

b. <u>DPCA (Displaced Phase Center Array) processing (fig. B37)</u>

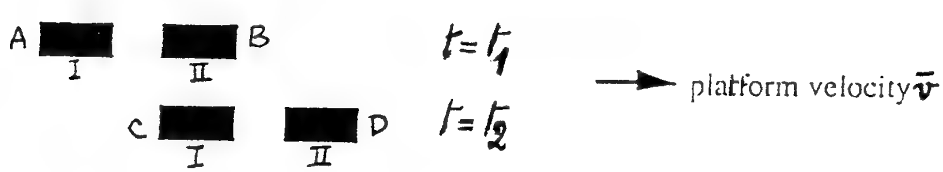


Fig. B37. DPCA processing

DPCA processing uses two (or more) antennas I and II arranged in tandem (fig. B37).
At time t_1 the 2 antennas occupy the positions A and B. At time t_2 the 2 antennas occupy the positions C and D. By controlling the radar PRF as a function of platform velocity v, it is possible that position B of antenna II at time t_1 coincides with position C of antenna I at time t_2. So by transmitting alternately and controlling the radar PRF as a function of platform velocity v, it is possible to obtain echoes from identical positions, but displaced in time (fig. B37). If one echo is substracted from the other (e. g. , substract signal II at position B from signal I at position C) , stationary targets should cancel, but echoes from moving targets will give a non-zero result from the substraction, so should remain. Coe and White have carried out a theoretical and practical evaluation of this technique. They found that cancellation of the order of 25dB is possible. The major source of error are control of the PRF (to give exact spatial coincidence of the samples), and matching of the antenna radiation patterns.

B.8. Optical Processing.

The most general structure of the SAR depicted by fig. B38 remind us that the signal processing is always performed in the baseband, i.e. , on the bipolar video, and that the signal processing can be

- either a digital one, which we discussed in the previous paragraphs
- or an optical one (in that case the bipolar video is fed to a CRT) which we are going to describe now.

The VCO realizes both the AM (chopping the microwave signal from the STALO into pulses with the appropriate PRF) and the FM within each pulse.

Prior to the optical processing, the bipolar video needs to be stored on a moving film; but a film can only record light intensities and light intensities (out of CRT for instance) are always positive or zero! As shown by fig. B38 the echoes are downconverted (by means of the PSD) to baseband and the obtained bipolar video $s(t) = \cos\phi(t)$ at the output of the PSD is used to intensity-modulate a CRT display. Since the bipolar video $s(t) = \cos\phi(t)$ at the output of the PSD is essentially an unbiased one-i.e. , the average value is zero-as shown by fig. B39, the negative values of this unbiased bipolar video s(t) would not be taken into account and would not be stored on the moving film.

Therefore, the baseband radar echoes are placed on a bias level s_b - giving thereby the biased bipolar video $[s(t) + s_b]$ depicted by fig. B40 - prior to recording on the moving film, in order always to have positive values at the input of the CRT.

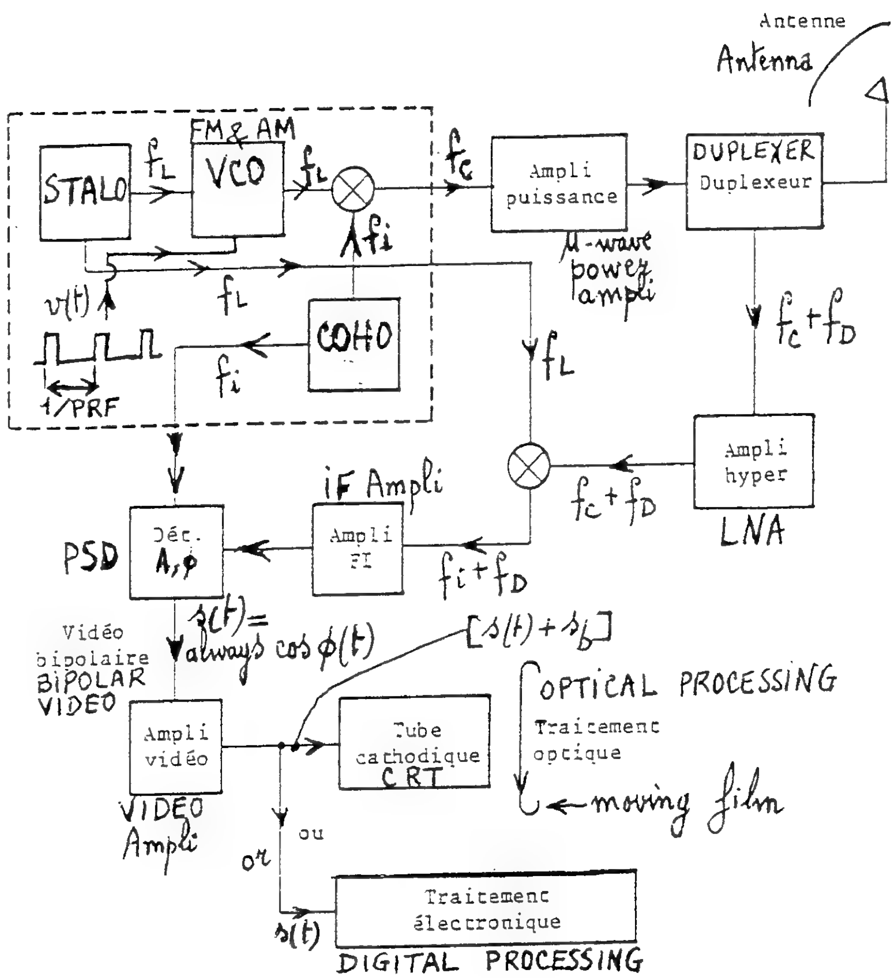


Fig. B38. General layout of the SAR hardware (p.295, THOUREL)

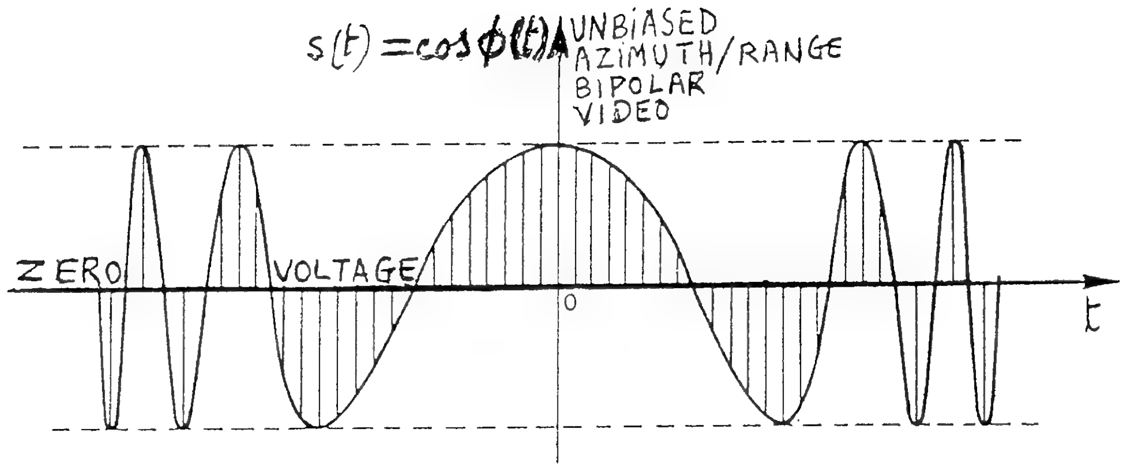


Fig. B39. Usual (unbiased) bipolar video at the output of the PSD of the radar layout of fig. B38.

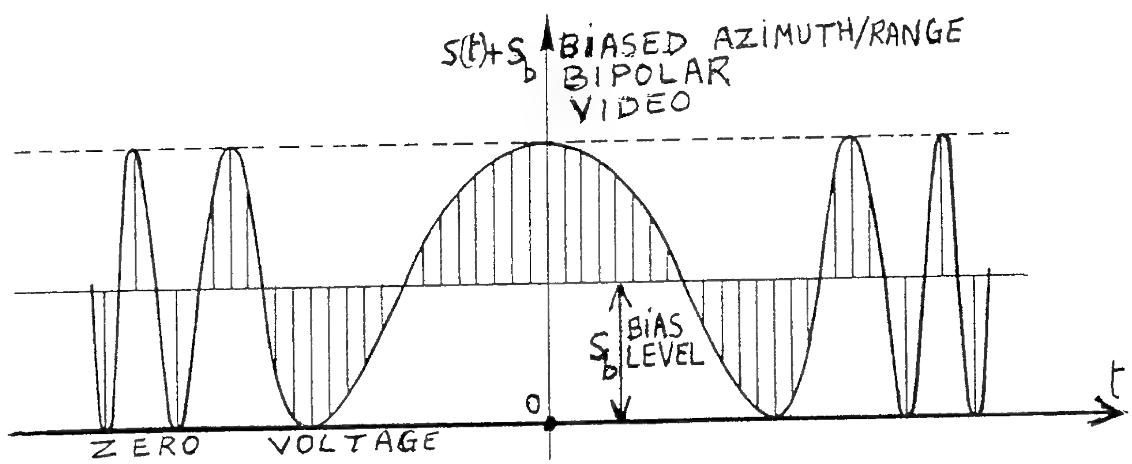


Fig. B40. Biased bipolar video to be applied to the CRT for recording on a film for later optical processing.

Therefore (see fig. B41) , the biased bipolar video $\left[s(t) + s_b\right]$ of fig. B40 is fed to the input of the CRT and intensity modulates the screen of the CRT in front of which the storage film is moving. So each echo is recorded as one line on a strip of the film, and successive echoes (emanating from successive transmitted pulses) are recorded as neighbouring lines.

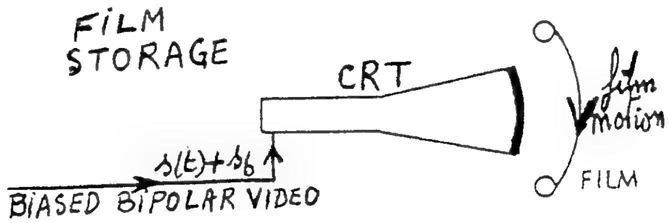


Fig. B41. Film storage through intensity-modulation of a CRT by the biased bipolar video $[s(t) + s_b]$

In other words, the radar receiver output is a sequence of reflected range pulses emanating from the transmitted pulses. The radar receiver output (i.e. , the output of the PSD on fig. B38) is placed on a bias level s_b, (cfr fig. B40) before being used to modulate the intensity of the sweep of the CRT (Cathode Ray Tube) , a single sweep being generated by each radar transmitted pulse, i.e. , the electron beam of the CRT (fig. B41)
is swept in synchronism with the returning pulses. The film moves (cfr fig. B41) across the screen of the CRT; the speed of the film is directly proportional to the radar platform velocity. Consequently, successive range traces are recorded side by side producing (cfr fig. B42) a two-dimensional format in which the dimension across the film represents range, and the dimension along the film corresponds to the along-track dimension, i.e., the azimuth coordinate x.

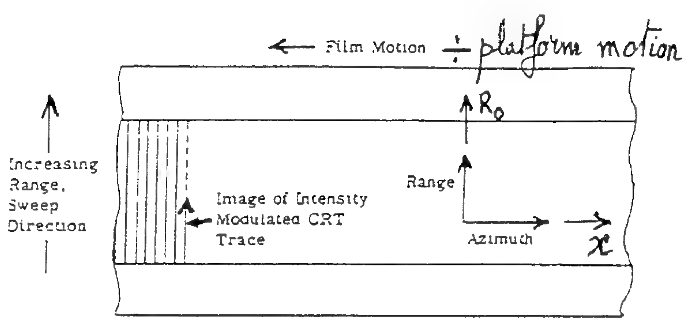


Fig. B42. Radar signal storage format

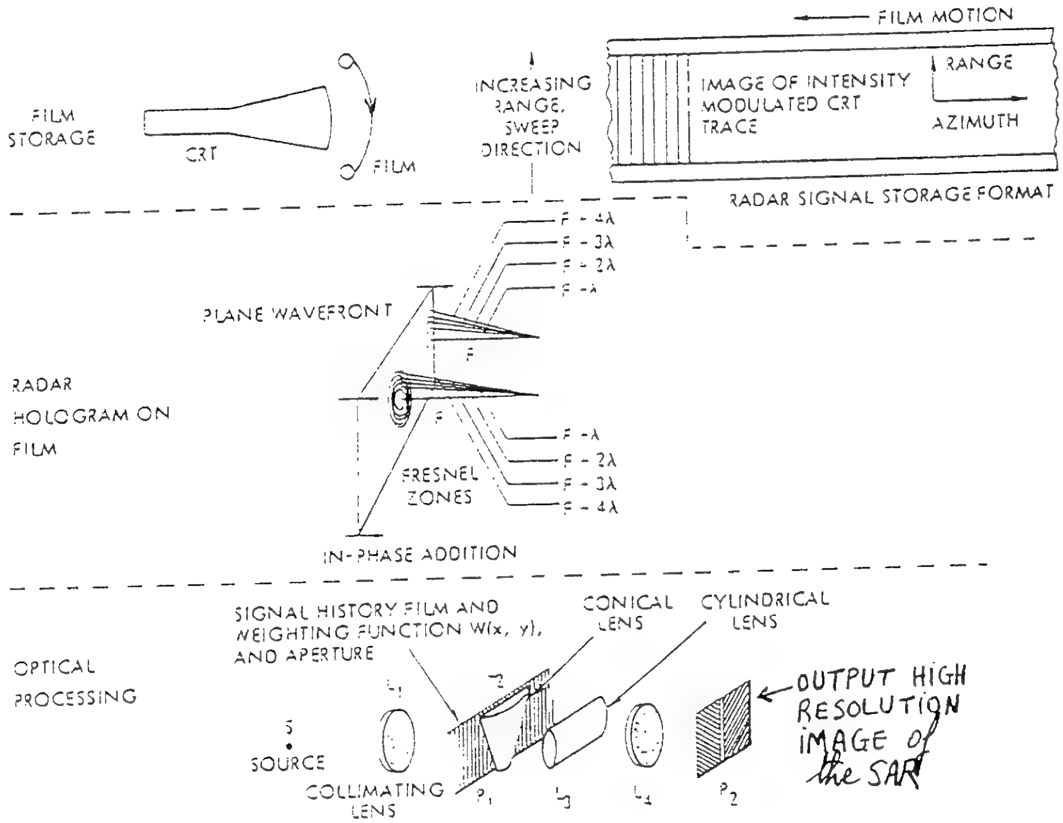


Fig. B43. Simultaneous Pulse Compression and Beam Sharpening (Optical Processing)

Fig. B43 both summarizes the essentials of optical type processing and introduces new terminology. A single sweep is generated across the CRT; the output of the radar's coherent detector PSD (see fig. B38) is used to modulate the intensity of this sweep.

The film moves across the tube; the speed of the film is directly proportional to the platform velocity. The lines are packed on the film so that there is some overlap. The phase history of the backscattered energy is stored on this film; the phase history within each echo pulse is stored in range dimension. When stored on the film, these phase histories have been characteristically called radar holograms owing to their similarity to optical holograms.

An image film from the signal film is produced in the optical processor, which typically is constructed with the elements shown in the lower diagram of fig. B43. A coherent source (thus, preferably, a laser source) of light (collimated to form a plane wave) shines on the signal film which contains the radar hologram; the conical lens L_2 has a (range) varying focal length to compensate for the phase variations in range. Because there is a different focal length for each

range element, a cylindrical lens L_3 is used to bring all of the range information into focus in one particular plane. Since the film recorded in front of the CRT of fig. B41 is processed on the ground, the optical processing is not a real time one. But, since 1995, several companies are giving a new life to optical SAR processing by replacing the film by spatial light modulators (also termed "light valves") enabling thereby a real time optical SAR processing.

Fig. B44 gives a better view on the whole optical SAR processor composed

- first of a conical lens L_2 performing the azimuth compression.
- secondly of a cylindrical lens L_3 performing the range compression

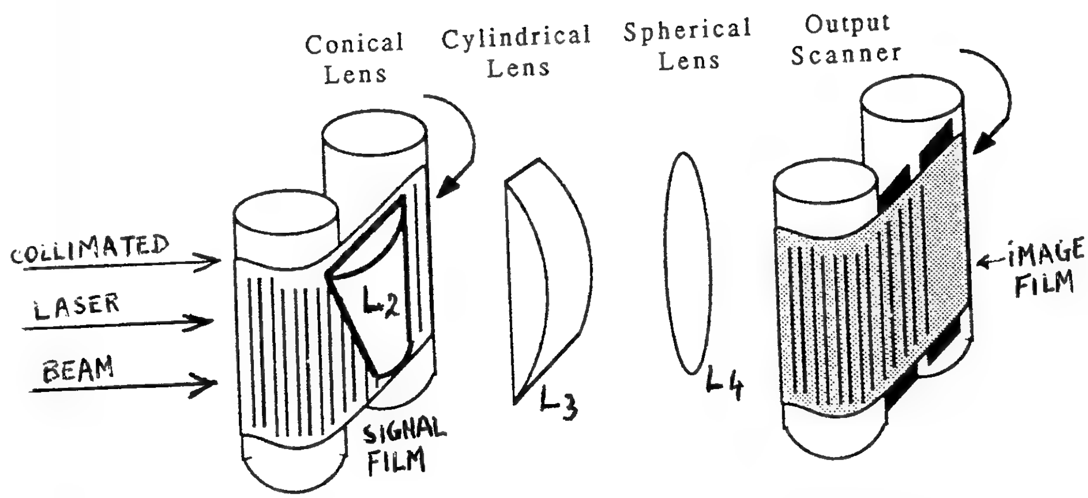


Fig. B44. Optical correlator for optical SAR processing (after BARBIER)

After the conical lens L_2 and the cylindrical L_3,the rays are collimated, i.e. , the rays are parallel. Therefore a spherical lens L_4 is needed to focus all those rays into a very small pixel (ideally focusing into a single point, as shown by the upper image of fig. B17)

It can be easily understood why a conical lens is needed for azimuth compression by looking to figure B15 which shows that the recording of the phases of the successive echoes (emanating from the successive transmitted pulses) from the same point-target P is equivalent to a plane-concave diverging lens whose concave diopter is nothing else but the iso-range line of fig. B15. Clearly, fig. B15 shows that the focal length of this equivalent diverging lens is depending on R_0, the target range at closest approach, which is also the radius of curvature of the concave spherical diopter of this diverging lens.

Since azimuth compression (i.e. , the realization of the synthetic aperture) requires the compensation of the phases $\left[-\frac{2\pi}{\lambda}.2R_i\right]$ recorded at the sequential positions E_i of the single SAR antenna, it is clear that this azimuth compression can be done by the opposite lens of the equivalent diverging lens, thus by a converging lens exhibiting a range depending focal length, which is nothing else but the conical lens L_2 of fig. B44.

A detailed working of the optical SAR processor of fig. B44 can be explained as follows.The three lenses L_2, L_3 and L_4 form an anamorphic lens system.The conical lens L_2, having a focal length equal and opposite to that of the signal films, operates on the azimuth focal plane and moves it to infinity. The azimuth focal plane thus becomes erected. The cylindrical lens operates only in the range dimension and images the signal film plane at infinity. The sperical lens, operating in both dimensions, takes the image at infinity and reimages it at its focal plane, where the image is now sharply focused in each dimension.

B. 9. Spotlight Mode and other High Resolution SAR's.

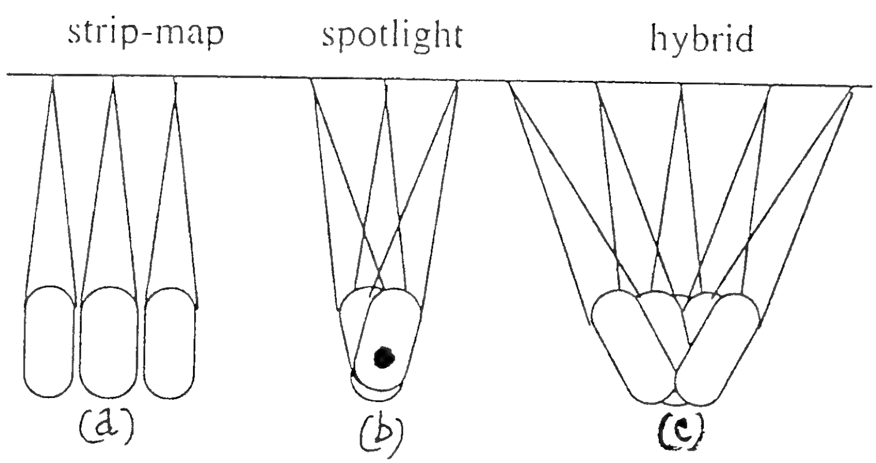


Fig. B45. Strip-map,spotlight and hybrid imaging modes (after Belcher and Baker) where the big black dot of spotlight is the rotating point.

The conventional mode of SAR image formation as described in the previous paragraphs is know as STRIP-MAP mode.As we have seen, the strip-map mode uses (cfr fig. B45.a) fixed broadside antenna pointing, i.e. , in the strip-map mode the SAR antenna beam points perpendicularly to the platform path (fig. B46.a).

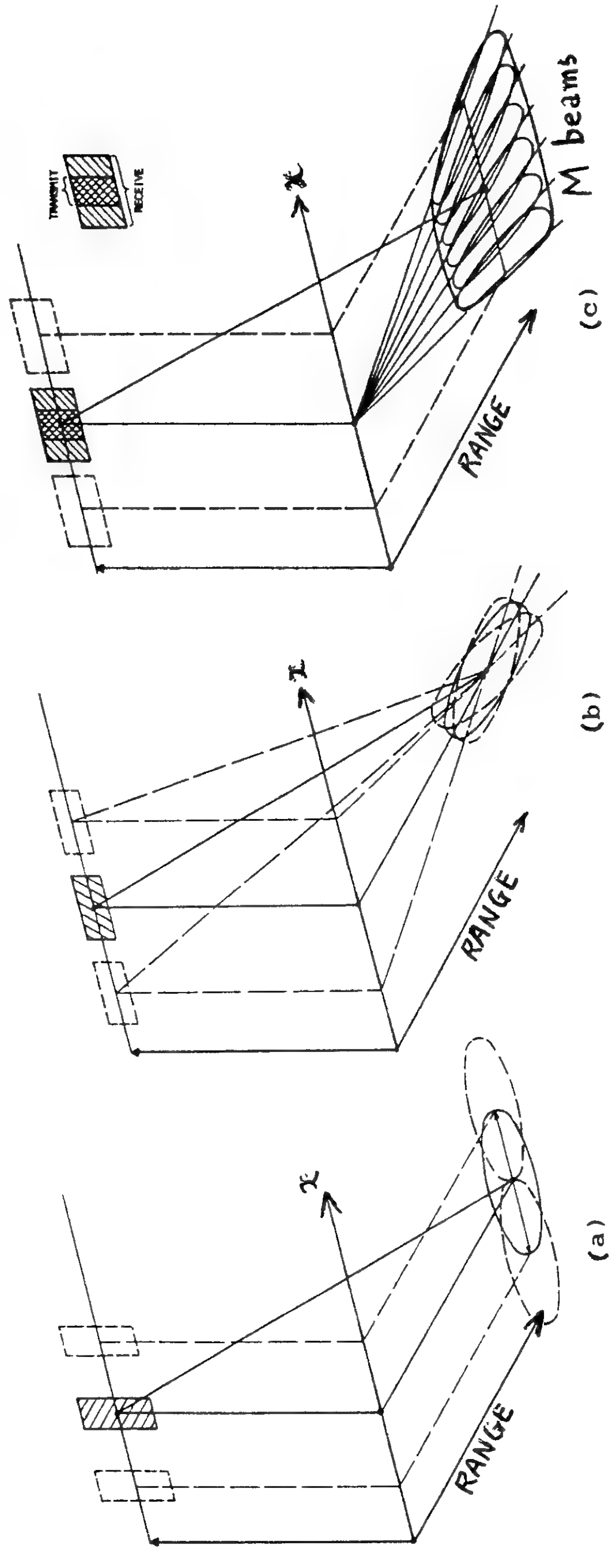


Fig. B46. <u>High Resolution SAR concepts in azimuth</u>

(a) Regular SAR, i.e. , strip-map mode ; (b) Spotlight SAR

(c) Multibeam SAR

If the SAR antenna is steerable in azimuth (either mechanically or electronically), it is possible (see figures B45.b and B46.b) to steer the antenna beam so that a particular target is illuminated for a longer period of time (i.e. , a longer dwell time), thereby allowing a longer aperture to be synthesized (since the synthetic aperture length is the path travelled by the sensor during the dwell time) and achieving better azimuth resolution δAZ than implied by the equation

$$\boxed{\delta AZ = D/2}$$

which is valid for a strip-map SAR.

It can be shown that the maximum azimuth resolution achievable in spotlight mode (if the antenna beam can be steered through 180°) is equal to

$$\boxed{\delta AZ_{spotlight} = \lambda/4}$$

In practice this is unrealistic (because the antenna beam can obviously not be steered through 180°) though considerably better resolution than strip-map mode can be achieved in spotlight mode.

It is possible (see fig.B45.c) to consider a hybrid mode of operation, intermediate between strip-map and spotlight modes.

Of course, spotlight mode demands that the target scene of interest is know beforehand, and only this scene is imaged.

As a summary, it may be claimed that a "spotlight" mode SAR directs the antenna to a single spot over and over again as the antenna passes high above. In the "spotlight" SAR mode, the synthetic aperture length L (which is the sensor path travelled during the dwell time) is drastically increased by pointing the steerable SAR antenna to the small area of interest during the fly-by.

Another method of achieving a high along track resolution (i.e., a high azimuth resolution) is to implement the well know multi-beam phased array radar as shown in figures B46(c) and B47. If M beams are formed simultaneously (M = 3 in the case of fig. B47), it is quite obvious from fig. B46(c) that the multi-beam SAR exhibits an M time finer along track resolution, i.e., for the multi-beam SAR (with M simultaneous beams)

$$\delta AZ = \frac{D/2}{M}$$

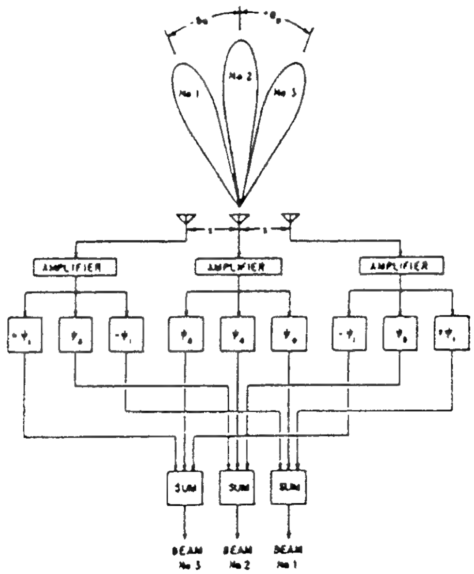


Fig. B47. Simultaneous postamplifier multibeam formation using array antenna.

B. 10. Swath Width.

As shown by fig. B48 the swath width AB is linked to the 3dB elevation beamwidth θ_{EL} of the SAR antenna and to the range R_0 at closest approach.

Since θ_{EL} is a small angle, $AC \approx R_0.\theta_{EL}$ and $AB \approx AC/\sin\Delta$ where Δ is the depression angle. Hence the swath width $AB \approx R_0.\theta_{EL}/\sin\Delta$

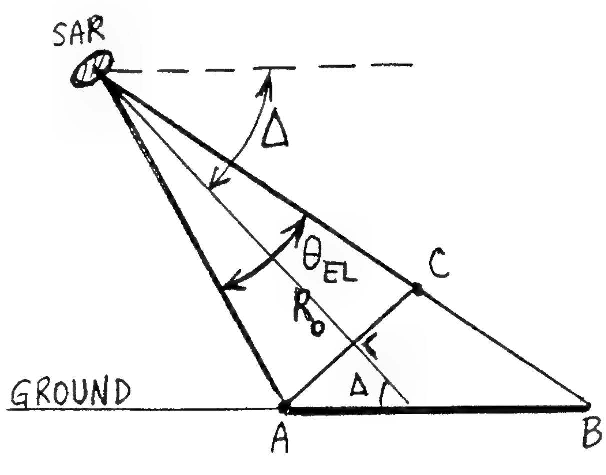


Fig. B48. Swath width AB and depression angle

B. 11. Special SAR's Characteristics and Working Modes.

a. Speckle

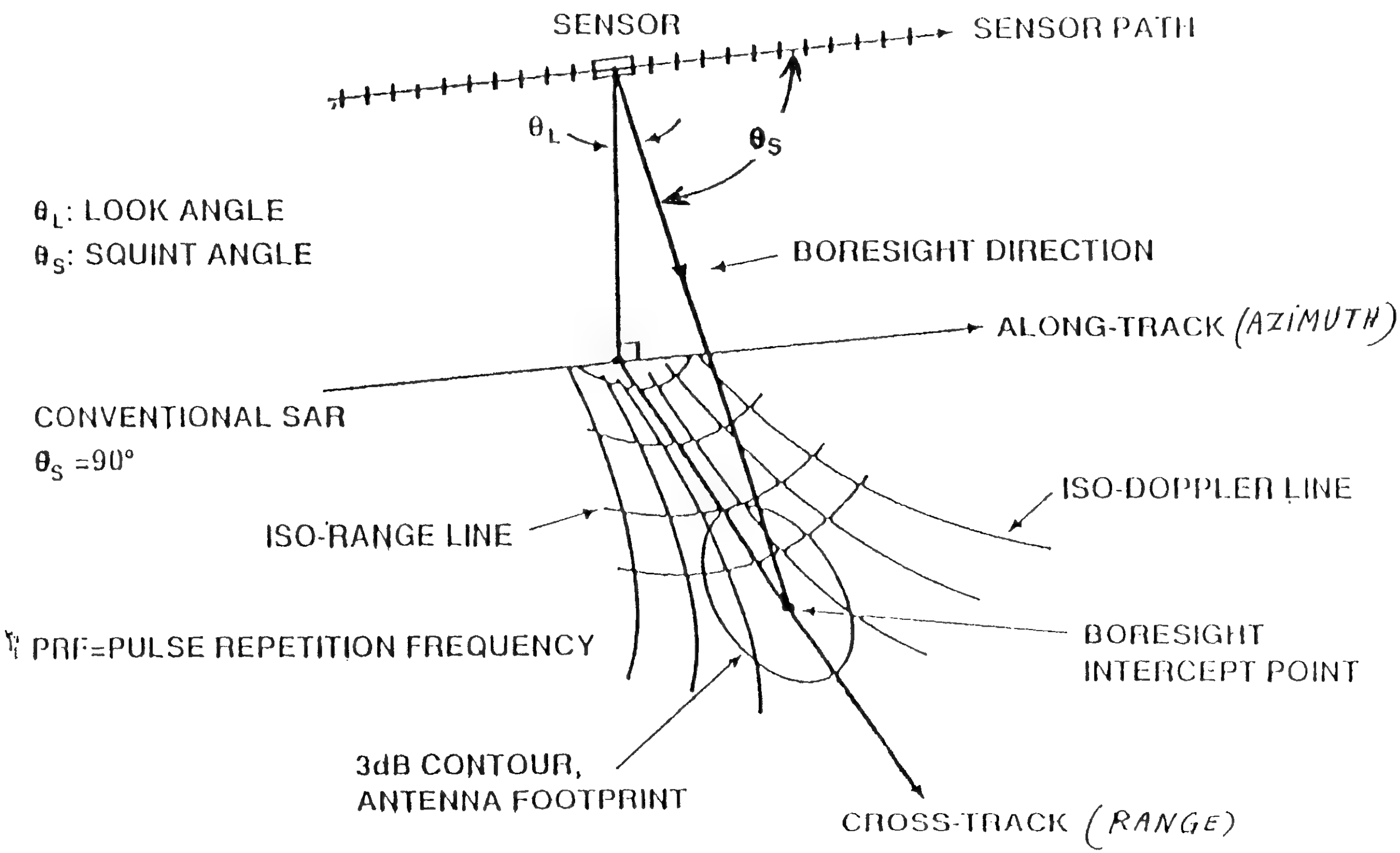
Speckle is the "grainy" appearance of radar images. Speckle is caused by a combination of scattering from lots of small scatterers within a pixel, i.e., speckle is a scattering phenomenon which arises because the resolution of the sensor is not sufficient to resolve individual scatterers. It is not limited to SAR: speckle can also be seen by looking to the reflection of an expanded laser beam on a "smooth" wall.

b. Squint angle and squinted SAR mode

In the conventional strip-map SAR, the antenna is fixed, pointing purely broadside with respect to the platform (or sensor) path. In the squinted SAR mode, the antenna is also a fixed pointing one, however (see fig. B49 where the squint angle θ_s is different from 90°) the antenna pointing direction in azimuth is not longer perpendicular to the sensor path but squinted by a positive or negative angle θ_s called squint angle (in a conventional strip-map SAR, $\theta_s = 90°$). The squinted SAR mode could be of interest in a multi jammer environment to look through the individual jammers. Another advantage of this mode could be a "mapping ahead" capability.

SAR PROCESSING

FIG. B49. SAR MAPPING GEOMETRY



c. Unfocused synthetic antenna

The conventional strip-map SAR with azimuth resolution $\delta AZ = D/2$ was previously called "focused synthetic antenna". Only from a historical viewpoint, it is worthwile to mention the so-called

"unfocused synthetic antenna"

which is nothing else but the well known "Doppler beam sharpening" featuring an azimuth resolution

$$\boxed{\delta AZ = \frac{1}{2}\sqrt{\lambda . R_0}}$$

(given by curve B of fig.B50)

to be compared with the azimuth resolution

$$\boxed{\delta AZ = \lambda R_0 / D}$$

(given by curve A of fig.B50)

of a conventional SLAR
and the azimuth resolution

$$\boxed{\delta AZ = D/2}$$

(given by curve C of fig.B50)

of the strip-map SAR (or focused synthetic antenna)

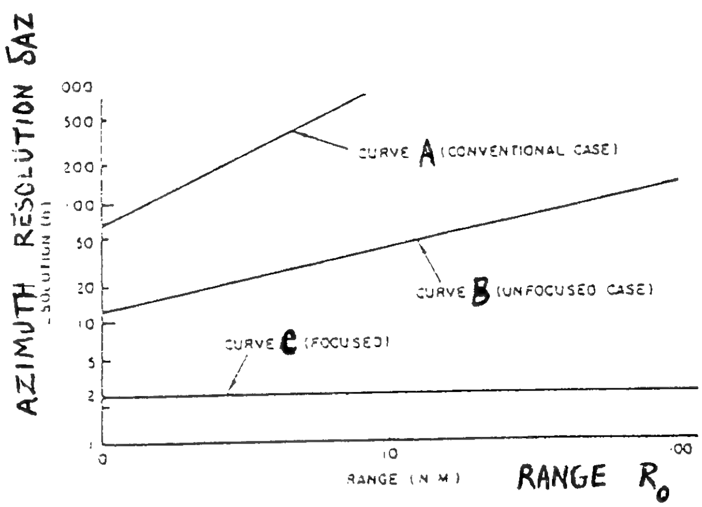


Fig. B50. Azimuth Resolution for Three Cases (A) Conventional (B) Unfocused, and (C) Focused

d. ISAR (Inverse Synthetic Aperture Radar)

Instead of using a moving radar to perform imaging of stationary targets, the radar can be held stationary and the target is moving.One distinguishes

- cooperative ISAR
- non-cooperative ISAR

Commonly the term ISAR is used to refer to a configuration where the radar is fixed and the target moves relative to the radar. A special case in this sense is the imaging of rotating targets without

transversal velocity components. In this configuration, the theoretical cross range resolution limit is given by

$$\boxed{\rho = \frac{\lambda}{2}.\delta\Omega}$$

It depends on the wavelength λ and the observation angle $\delta\Omega$ only.

e. Synthetic aperture sonar

Sonars and radars have wavelengths λ of the same order. But the sonar wave velocity is 200,000 times smaller than the radar wave velocity. Additionally, water salinity and temperature influence the sonar wave propagation. Synthetic aperture sonar systems are about 15 years behind the SAR's; nevertheless they are interesting to find mines on the sea bed; usually those mines have a big shadow behind the mine.

Acknowledgements
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The B-HUNTER UAV System

(October 1999)

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Abstract

The purpose of this paper consists to provide a general overview of the B-HUNTER UAV System that has been chosen by the Belgian Army Ground Forces. From year 2001, the B-HUNTER UAV system will replace the Epervier UAV System which was in use in the Belgian Army since more than 20 years.

The B-HUNTER UAV System is derived from the US Short Range HUNTER Tactical UAV that has been developed and qualified according to the most severe NATO requirements by a joint venture composed of Israel Aircraft Industries Ltd. (IAI) and TRW Inc. It has been recently successfully deployed in Kosovo operation with proven operational results that have been reported in profusion of press releases.

This paper will describe the main upgrades at system and subsystem level that will be performed in the frame of the Belgian Contract by the Belgian EAGLE Temporary Association. The B-HUNTER UAV system and subsystem are described.

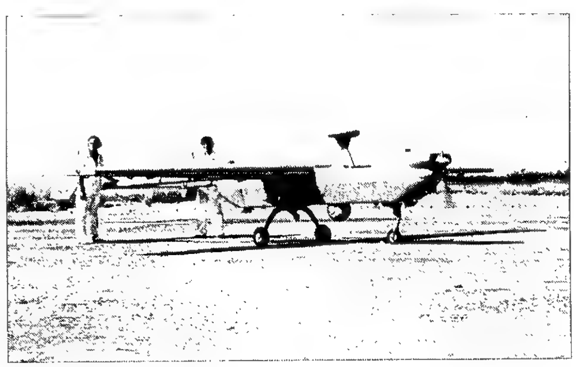
In the course of the B-HUNTER UAV Program, a lot of attention will be paid to the potential integration of the B-HUNTER UAV System in the civil air space. According to the Belgian law, UAV Systems have to comply with the following overall safety objective : "The B-HUNTER UAV System must allow during all its life safely execution of UAV missions above populated areas taking into account Belgian environmental conditions". A short introduction to the activities performed in the frame of the B-HUNTER UAV program with regards to airworthiness issues is presented.

Introduction

1.1. The heritage of the B-HUNTER.

The operational success of the B-HUNTER comes from the heritage of the developments of UAV by the MALAT Division of IAI started from 1974. In 1982, the first SCOUT UAV generation was used in mission in Lebanon by the Israeli ground and airforces. Second IAI-MALAT UAVs generation were deployed during the Gulf War with the US Government PIONEER Systems. These systems have also been extensively used during operations in Bosnia for peace keeping operations. The third generation of IAI-MALAT UAVs include the HUNTER Short Range Tactical UAV, the SEARCHER and other systems that fly today with success in more than 18 countries all over the world.

Seven HUNTER Tactical UAV Systems have been delivered to the US Army in 1995 after an extensive qualification program aimed to efficiently operate the system in all climatic and extreme meteorological conditions. The system as been extensively tested according to MIL-810 standards under the following conditions : altitude, rain, humidity, warm and cold conditions, salt environment, fog, dust and sand, road test , and rail impact.



The propulsion system has been subject to altitude and temperature tests according to FAR 33 standards from the Federal Aviation Regulations (FAR). These US Shrt Range HUNTER Tactical UAV Systems are now used by the military intelligence 15th battalion of the III US Corps and are currently successfully deployed in Kosovo

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operations.

More recently a modernised F-HUNTER UAV System has been purchased by the French ground and airforces. It is currently used with success and has reached the same performances in terms of operational availability than the American system.

After a huge tendering process including extensive flight and ground evaluation tests, the Belgian UAV Contract of the Belgian Army ground forces has been awarded to the EAGLE Temporary Association in December 1998.

It is to be mentioned that three NATO countries have now chosen the HUNTER based UAV system with all the advantages that their choice could bring in terms of international cooperation, life cycle cost monitoring and commonalties for future improvements.

1.2. B-HUNTER UAV System major improvements

Since its original conception, major improvements have continuously been made on the original HUNTER System which is today a proven system in the fields of software, aids to mission planing, use of ground control stations and interface with modern tactical communications.

New improvements of the HUNTER UAV System will be made in the frame the B-HUNTER UAV Program ordered by the Belgian Ground Forces. These include :

- Implementation of a new airborne avionics computer
- Automatic Take-Off and Landing System
- Fourth Generation Ground Control Station with upgraded mission planning and control software
- Integration within the Belgian Army infrastructure (tactical communications, reporting to Intelligence echelon, ...)

While still complying with the environmental requirements, where ever it is possible, it will be called to extensive use of Commercial Of The Shelve (COTS) equipment as well as Non Developmental Items (NDI), in order to reduce the life cycle cost.

These improvements will be performed by the EAGLE Temporary Association constituted under the Belgian law of Israel Aircraft Industries Ltd., SAIT Systems – Brussels, SONACA – Charleroi, THOMSON-CSF Electronics Belgium – Tubize and THOMSON-CSF Systems Belgium – Antwerpen.

B-HUNTER UAV System Description

2.1. System Overview.

The B-HUNTER UAV System is designed to be utilised in the Belgian Armed Forces for information gathering in threat environments that pose risk to a manned or piloted air mission, or where extended surveillance mission times are required. The system is based on the HUNTER system that has been fielded by the US Ground Forces.

Information is gathered by the system for intelligence, target acquisition, and battle damage assessment. The information is returned to the ground station via a full duplex RF link operating in the C band.

The B-HUNTER UAV System is capable of being operated, maintained, transported and deployed as a self-contained system. Each B-HUNTER System comprises the following:

- 6 B-HUNTER UAVs (including airborne communication and IMINT payload)
- 2 Ground Control Stations (GCS)
- 2 Ground Data Terminals (GDT)
- 1 Lot of Integrated Logistic Support (ILS)
- 1 Lot of Ground Support and Test Equipment (GSTE)

Additionally, a total of five (5) Portable Ruggedized Control Stations (PRCS) and two (2) Operator Proficiency Trainers (OPT) are provided.

Figure 2. depicts the major components and interfaces of the system.

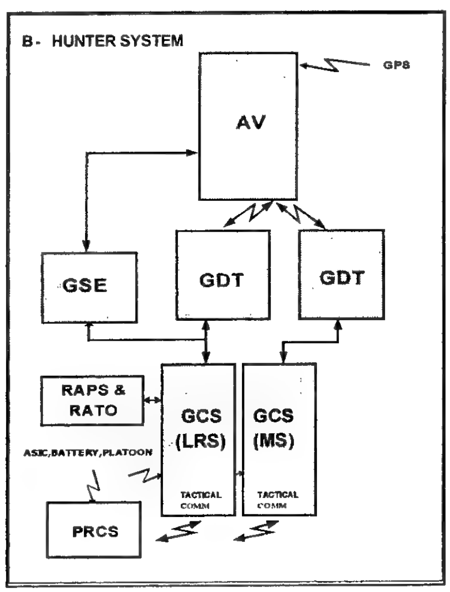

Figure 2. B-HUNTER UAV System Major Components

The UAV is a twin engine, fixed wing configuration. It

is either flown remotely from the GCS or autonomously using a predetermined flight plan.

The UAV is capable of carrying a payload to accomplish the system's missions. The payload is a dual sensor configuration using a CCD camera and a FLIR, thus capable of operating in both day and night. The payload provides Real-time video images to the GCS, via the GDT. The video images and target position data from the system may be used directly by commanders at the ground or relayed to external Command-Control-Communication Information systems (C3I).

The flight path for specific missions may be pre-determined by specifying waypoint coordinates on a map displayed by the mission planning computer in the GCS. Using digitized maps, waypoints and flight times are specified to create a flight plan. Payload control commands are determined to carry out the specified mission. The mission, air vehicle and payload commands are downloaded to the air vehicle mission computer during the pre-flight procedure.

Any of the pre-programmed flight commands, stored in the UAV mission computer, may be overridden or changed by the air vehicle operator at the ground control station during flight. New waypoints may be specified and Real-time operation of the payload can be provided by the payload operator.

The UAV takeoff is either a conventional runway takeoff or by launching, using a RATO launcher. Both methods use the ATLS to accomplish an automatic process. The UAV is automatically landed by the Automatic Take-Off and Landing System (ATLS). In case of an emergency, the recovery is by using a parachute.

The B-HUNTER UAV System is capable of deployment in two sites:

- Launch and Recovery Site (LRS) – Figure 3.
- Mission Control Site (MCS) – Figure 4.

The sites may be at a distance limited by the Belgian tactical communication range.

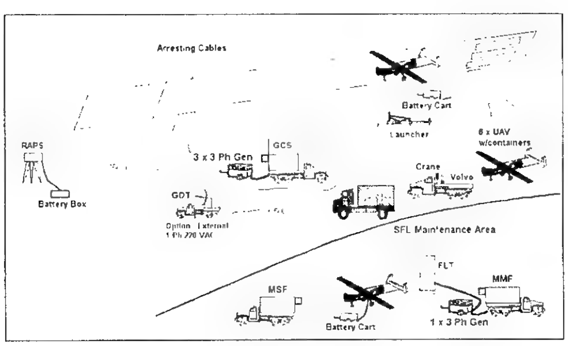

Figure 3. - Launch and Recovery Site

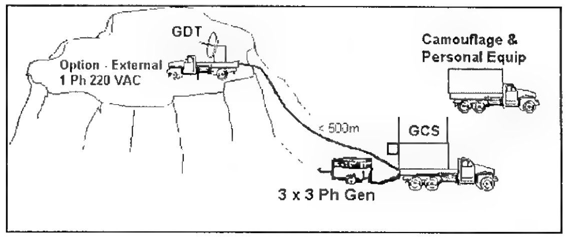

Figure 4. Mission Control Site

The B-HUNTER UAV system will meet the requirements concerning Security, Hygiene, Embellishment and the legislation concerning the Environment, as apply to military equipment and foreseen in the RFP and the proposal.

2.2. Missions

The UAV System will be capable of fulfilling the following missions :

- Imagery Intelligence (IMINT) Combat Information with day/night capability
- Damage Assessment with a day/night capacity
- Target Acquisition
- Artillery Adjustment

The main tasks of the IMINT combat information for the division consist of locating the reserves, the headquarters and the artillery positions of the enemy through the interpretation of images. The UAV System will also have the capability of performing the following tasks :

- Gathering information about certain parts of the terrain
- Gathering information about infrastructure having military importance
- Localization and attitude of enemy units
- Confirming information gathered by other means
- Directing the search for other means of information
- Delivery of proof through images
- Zone surveillance
- Border surveillance
- Control of disarmament agreements
- Following movements of troops and refuges
- Escorting of columns

In the Damage Assessment mission, the UAV System will supply continuous and reliable information to the division level relating to the results of the fire support.

For Target Acquisition missions, the UAV System will provide continuous and reliable information to the division level relating to the detection and the acquisition of possible targets for support in depth, in order to make accurate localization of enemy command posts, liaison centres, logistic installations, rocket launching ramps, AA and AT units and reserves.

For Artillery Adjustment missions, the UAV System will

provide reliable information to the fire control centre of the supported field artillery unit relating to the distance (in meters) between the effect of one artillery shot and the target.

2.3. Operators and Tasks

The main operational tasks are :

- Mission Commander
- Mission Planner
- Pilot Navigator
- Real Time Observer
- Off Line Analyst
- Field Operators

Each one of these main tasks comprises either real-time tasks or off-line tasks; the real time tasks are the Pilot Navigator and the Real Time Observer tasks, the off-line tasks are the Mission Planner and the Off Line Analyst tasks, while the Mission Commander tasks are divided into real-time tasks and off -line tasks. Three operators will manage the tasks as follows:

- Operator No. 1 - Mission Commander, Planner and Off Line Analyst
- Operator No. 2 - Pilot Navigator
- Operator No. 3 - Real Time Observer
- Operator No. 4. – Field Operators

The Mission Commander, Planner and Offline Analyst will have the following capabilities :

a) Functions Commander:
   - Receive in the GCS the alphanumeric Operation Order (OO) containing the necessary data
   - Evaluate in the GCS the tactical situation through a Tac Sit overlay received in the framework of the operation order (threat, meteo. data, etc.)
   - Monitor the execution of the flight mission and take the necessary action in case of an emergency situation.
   - Inform the responsible operators of the UAV System and its higher echelon concerning the conduct of the flight mission so that the necessary measures can be taken to adjust the mission, to correct the execution of future missions and/or to analyze eventual human errors and/or failures of the material during the executed mission.

b) Planner Functions :
   - Make a correct plan of the flight mission, including overlay updates, route planning and route analysis (this function can also be performed by the Pilot Navigator)

c) Off-line Analysis Functions:
   - View real-time video
   - Capture still images
   - Visualize and interpret the already captured images (analog video from playback and stills) of an earlier or an ongoing mission
   - Transmit the relevant information (intrep, overlays, still images) from the captured images to the higher echelon Branch 2.

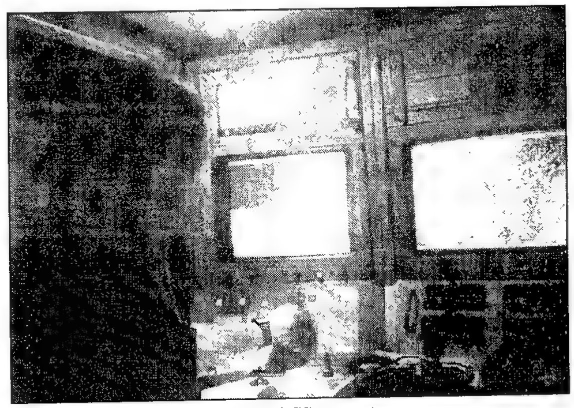

Figure 5. : GCS operations

The Pilot Navigator has the capabilities required to execute and follow up the flight mission, including:

- Perform self test of his console and the GDT
- Perform Pre-set procedure of the flight associated data
- Update Overlay data
- Plan flight routes, analyze them and load to the UAV
- Monitor the UAV launch, and systems during flight
- Select the flight modes and steer the UAV
- Operate the UAV sub-systems
- Perform emergency procedures

The Real Time Observer will have the capabilities required to execute and follow up the flight mission, including:

- Perform self test of his console
- Visualize real time images coming from the IMINT payload
- Control all IMINT payload functions and operational modes
- Monitor payload status
- Annotate images for later analysis by the Off-Line Analyst (this capability is also available for the Off-Line Analyst)
- Annotate items of interest on the image for later analysis by the Off-Line Analyst (this capability can also be performed by the Off-Line Analyst)
- Steer the UAV

The Field Operators in the LRS Site are responsible for

testing of the UAV, preparing it for launch, setting up the Auto-land sensor, post flight activities and other activities concerning the operation of the UAV and the security of its operation.

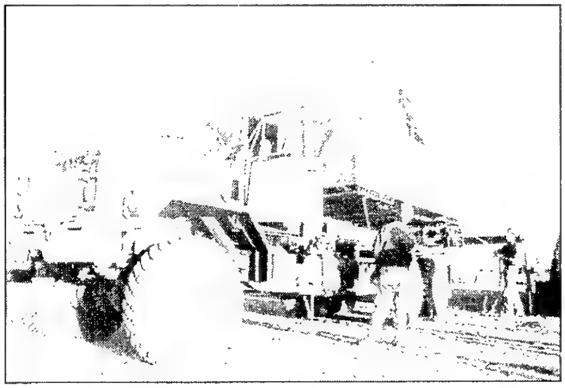

Figure 6 . Field Operations

2.4. Modular Optronic Stabilized Payload (MOSP)

The MOSP is a IAI-TAMAM stabilized passive electro-optical system, variable line of sight, designed to provide the observer with the capability for acquiring and tracking targets under day and night conditions.

Figure 7 . Field Operations

The MOSP payload:

- Enables the operator to acquire targets during day and night engagements.
- Provides the capability to track targets either manually by using a joystick or automatically by using the TV tracker with either Camera Lens Assembly (CLA) or Forward Looking Infra Red (FLIR) sensor as image source.
- Provides the capability to select between the CLA image and the FLIR image.
- Provides Line of Sight (LOS) direction (bearing and depression) in reference to the UAV axes.

Its main technical performance allow to the following :

- Video tracker
- FLIR and CCD sensor capabilities
  - Detection (NFOW) : > 7.5 km
  - Detection (WFOW) : >5 km
  - Recognition : > 2.5 km
  - Identification : > 1.5 km

2.5. Data-link

The B-HUNTER UAV System employs primary and secondary (back-up) uplink communication channels and one downlink (wideband). The same frame format is used by the primary and backup channel, through each of the operational phases described below. The UAV employs an emergency logic in which the functional uplink replaces the malfunction uplink, as the active controlling channel, in case of UAV control channel failure (either primary or backup).This logic is implemented through all operational phases of the UAV.

a. Operational Modes (Takeoff / Landing / Mission)

The UAV communication system operates via the GDT and the ADT. During the Takeoff/Landing phase, omni antennas are used in both the UAV and GDT, while in the Mission phase, the GDT and/or UAV use directional antenna. The onboard transmitter and receiver are controlled by the DCPA

b. Uplink Backup Operation

Both primary and backup channels are suitable to serve as the UAV sole controlling channel (distance dependent). Normally, both uplinks are continuously transmitted by the GDT and received by the UAV, constituting a "Hot Backup Logic" within the UAV. The functional uplink channels immediately replaces the malfunction uplink, as the active controlling channel, without the need for re-synchronization. This backup operation automatically occurs in case of malfunction in the controlling channel.

c. UAV Hand-over

In this phase, UAV control is transferred between the GCS of the MCS and the GCS of the LRS and vice versa. This process is performed while both stations receive downlink channel (via the UAV omni antenna). At a start of a mission the GCS of the LRS controls the UAV via the primary channel and the GCS of the MCS communicates with the UAV via the backup channel. The process starts when the GCS of the MCS requests the UAV to grant control via the backup channel. The process is accomplished when the GCS of the LRS approves the request. Both uplink channels, primary (UPL_1) and backup (UPL_2) are used for this Hand-over to assure continuous control during the change over.

d. Operator Initiated Change-Over

The operator can change, upon request, the controlling channel of the UAV from the primary channel to the backup and vice versa. This process is implemented simply by using the same logic of UAV hand-over in the frame work of one station.

2.6. Real Time Information and Command of the UAV

The B-HUNTER UAV system transmits the video from the payload in real time to the GCS. The operators in the GCS receive the video in real time. The UAV also transmits status information, concerning the flight and the payload, to the GCS in real time. The video and UAV status information are available whenever the UAV is within operating range of the GDT.

The mission console displays the video and the status information in real time to the operators. The mission console derives additional information from the down link data reported by the UAV.

The GCS enables the operators to command and control the IMINT payload and the flight of the UAV in real time as long as the UAV is within the operating range of the GDT.

The GCS can handle two UAVs : one "on duty" and one "inbound" or "outbound" under autonomous programmed flight.

2.7. Automatic Takeoff and Landing (ATLS)

The UAV System is equipped with an Automatic Takeoff and Landing System (ATLS). The ATLS supports automatic rocket launching, automatic runway takeoff and automatic landing. The ATLS process is controlled and monitored from the GCS by the Pilot Navigator (PN). The UAV is capable of taking off from a straight and level unprepared terrain area of 25x300 meters maximum. A Rocket Assisted Take-Off (RATO) launching – zero length launching - is used for takeoff whenever the takeoff area is smaller.

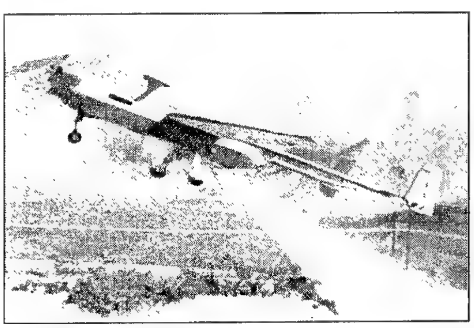

Figure 8. : RATO Take-Off

The UAV is capable of landing on a straight and level terrain area of 25x300 meters maximum. The surface at the two ends of the runway should be free of obstacles higher than 10 meters, at a distance of 200 meters from each end of the runway. The runway should maintain an appropriate leveling to support RAPS tracking capability.

The ATLS uses a Range Automatic Positioning Sensor (RAPS) to measure the UAV spatial location through a LASER retro reflector mounted on the UAV wing leading edge. The location data is provided to the GCS, through fiber optics cables. The OPBY at the GCS performs the Automatic Takeoff/ Landing (ATOL) geometric calculations and prepares the data for transmittal to the UAV where the DCPA performs the ATOL control laws and algorithms.

2.8. Emergency Recovery

The UAV is equipped with an Emergency Recovery System (ERS) based on a Flight Termination System (FTS). In the event of system failure which would preclude a normal recovery, the Flight Termination System (FTS) is activated. The FTS is activated by a manual command from the GCS or automatically in the event of loss of communication or total failure of the DCPA.

The DCPA is capable of initiating the emergency recovery process according to operator's command received through the ADT, or as part of the Loss-of-Link flight plan, independently, in the event of loss of communication. The Flight Terminal Logic (FTL) unit is capable of initiating the emergency recovery process in the event of a total failure of the DCPA itself. The FTL activates the FTS which performs: UAV payload Lift-up to safety position (Lift-UP command); Cuts UAV engines (FWD and AFT Engine Cut Command) and releases the parachute (Shoot Parachute).

2.9. System Built In Test (BIT)

The B-HUNTER UAV system is provided with BIT capability to decrease the time required for checkouts or fault isolation, and to provide status monitoring. The UAV, GCS, GDT and the MOSP are provided with BIT to detect failures and isolate the failures to the LRU level. The BIT is used to ascertain mission readiness status and to indicate which equipment is malfunctioning.

BIT features are provided in the electronic LRUs/DUs. The BIT operates in three modes: Power Up BIT, Initiated BIT and Periodic BIT.

Power Up BIT is initiated as power is applied to the

system/subsystem, and is capable of system/subsystem checkout and fault isolation to an LRU. Go/No-Go indication shall be displayed and the failure log shall be updated. Failure data is stored in the Non Volatile Memory (NVM) of the end item computer. Power Up also checks circuitry that cannot be tested during operation without interfering with normal system operation.

Initiated BIT is activated by the operator. The operator is guided by the BIT menus displayed on the GCS or the Flight Line Tester screens to check the functions that can be tested off-line only due to interference with the system operation and to perform functional tests after maintenance or during preflight or pre-operational tests. This mode is also used to display failure data. Failure data is stored in the NVM of the end item computer.

Periodic BIT is performed automatically, without interference to the system normal operation after initialization, as a background task of the system's normal operation. Periodic BIT detects and isolates failures that occur during system operation. Safety critical and mission critical failures are automatically displayed to the operator during system operation. Failure data is stored in the NVM of the end item computer.

2.10. Tactical Communications Network

The following tactical communication networks are realised in the UAV Platoon :

- Battery Technical Net
- Platoon Command Net
- Higher Echelon Intelligence Net

Figure 9. depicts the integration of the UAV system within the three tactical communication networks.

The Battery Technical Network is used to transmit the UAV operation orders from the Battery Commander to the UAV Platoons. In addition, it also enables transmission of tactical overlays from the Battery Commander. It is composed of QUICK DATA VHF BAMS radios for the Battery Commander and the three GCS Mission Commanders. The transmission includes the following :

a) Operational Orders (OO)
b) UAV RECCE Request
c) Warning Order
d) Movement Order
e) Free Text
f) Overlays for tactical maps.

Each VHF BAMS radio in this network is functionally connected with the respective mission console of the Mission Commander in the GCS and the PRCS of the Battery Commander.

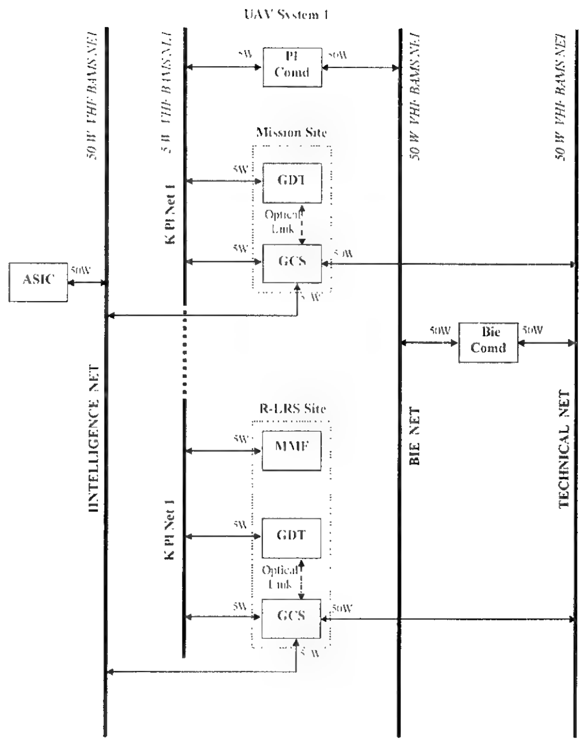

Figure 9 : Integration of TACOM Radio Networks within the UAV System

The Platoon Command Network is used to manage the UAV System. It is composed of a network of VHF BAMS radios for the ground elements (GCS, GDT, LRS) of each platoon and the S&TE for Single Field Level (SFL) Level maintenance. The VHF BAMS radios of this network are integrated in the corresponding elements of the UAV System. For each Platoon, the VHF BAMS radios connect, as a backup means, all of its elements and the S&TE level B3, by voice communication.

The Higher Echelon Intelligence Network is used to transmit the Intelligence data of the various UAV Platoons to the division ASIC, including fixed (still) images with overlaid data. It is composed of a network of VHF BAMS radios connecting the Division ASIC with the offline analysis in each GCS. The system transmits information obtained from the payload to the ASIC by the Intelligence network :

a) Intelligence Reports (INTREP) with text and numeric data. This information includes date and time, identification of target, coordinates of target.
b) Overlays of digital maps with graphical and alphanumeric (label) data
c) Single frame images from the IMINT payload. Each image is annotated with system data, and marked up with symbols and text. The images will be transmitted in JPEG format.

Each VHF BAMS radio of this network is functionally connected to the respective GCS (Mission console with the Off Line Analyst function) and the PRCS of the division ASIC.

The UAV System has also the capability to realise communications between its elements and to external authorities via telephone voice communications. Three field telephones are supplied for each system which interconnects with the intercom system.

There is also the possibility, as growth potential to integrate the UAV System in a Air Traffic Control (ATC) Network and in a Chase Heli Network.

2.11. System Performance

Operational Range

The operational range of the air vehicle, when there is a clear line of sight between the Ground Data Terminal (GDT) and the air vehicle, is 100 km.

Endurance

The Endurance as related to the flight profile is 10 hours (including reserve time of 30 minutes) with maximum fuel (takeoff weight 1600 lb). The UAV maximum loiter time above target (at 100 km range and same flight profile) is 7 hours.

Target Localization

When the UAV is at an altitude of 1000 m and at a slant range of 1500 m from the target, it measures the coordinates of the target in the UTM system relative to WGS 84 with an accuracy of 81 meters CEP. When the UAV is at an altitude of 1000 m and at a slant range 2500 m from the target, it measures the coordinates of the target in the UTM system relative to WGS 84 with an accuracy of 148 meters CEP.

UAV Localization

The UAV system uses the GPS receiver, located on board the UAV, as the primary method for UAV localization. As a secondary method, the UAV system tracks the air vehicle and provides its distance and azimuth measurements, in relation to the GDT location, to the operators. The distance accuracy in this method is 200 meters. It is possible to calibrate the distance and azimuth information in flight, or on the ground, by using the information provided by the UAV on-board GPS and the known location of the GDT.

Redundancy

The UAV avionics, the GCS and the Data Link have redundant hardware in cases where a component is critical for safety of the UAV. If a redundant item fails, the system can continue safe operation by using the spare hardware.

The system also has backup modes of operation that allow it to continue to operate in a degraded fashion following a non-critical item failure.

Autonomous Flight

The UAV is capable of performing pre-programmed mission profiles independent of GCS navigational guidance. The autonomous navigation is the normal navigation method during the flight. The pre-planned mission consists of a series of commands stored in DCPA to be executed in sequence when the UAV is operating under pre-programmed control. Each command in this series is defined as a waypoint and the mission planning is the end result of the series of commands. The commands include: UAV guidance, payload operation, communication control, etc. During operation, the way points serve as a destination for the UAV navigation system for the duration of that command. During autonomous flight, the GCS is constantly monitoring the down link received from the UAV.

Mission Continuity

The B-HUNTER UAV System can operate during 30 consecutive 24 hour days following user operational profile.

Data Link Performance

A communication range of downlink channel of at least 100 km between the GDT and the UAV in Line Of Sight (LOS) condition. Fail safe architecture is established in the ADT and the GDT by separating the Primary and the Backup terminals by means of function, power supply and communication with the DCPA/GCS.

The GDT is constantly transmitting via two up-link channels, each capable of serving as the UAV controlling channel. The UAV DCPA receives both the primary and the back-up channels and uses the functional channel by a "Hot Backup Logic".

The downlink contains either analog video or a digital compressed video signal as selected by the operator. In-flight selection of 7 pre-set frequencies (for each uplink or downlink link).

Co-existence of 3 UAVs controlled by their respective GDT is maintained by using adequate frequency separation among the uplink, downlink and back up channels, within the area of 70 km x 35 km and minimum separation of 300 meters between UAVs.

Inherent Availability

The inherent availability for the UAV System is calculated as 97.5 %.

Operational Availability
The operational availability for the UAV system is calculated as 71.6%.

2.12. System Deployment

The UAV System is deployed in two sites as depicted in Figure 3 and Figure 4. Figure 10. depicts the UAV System mobilization to the deployment sites.

Launch and Recovery Site includes:

- Six UAVs in containers
- One GCS
- One GDT
- Six IMINT payloads
- One Mobile Maintenance Facility (workshop, tent, storage space) with the associated Single Field Level support equipment and spare parts
- One RATO Launcher
- Take-off / landing area
- RAPS Sensor
- One Flight Line Tester
- Power supply generators, 3 12.5KVA (x4) - Government Furnished Equipment (GFE)
- Ground Support and Test Equipment.

Mission Control Site includes:

- One GCS
- Power supply generator, 12.5 KVA (x3) - Government Furnished Equipment
- One GDT (at up to 500 meters distance from the GCS)
- Ground Support and Test Equipment.

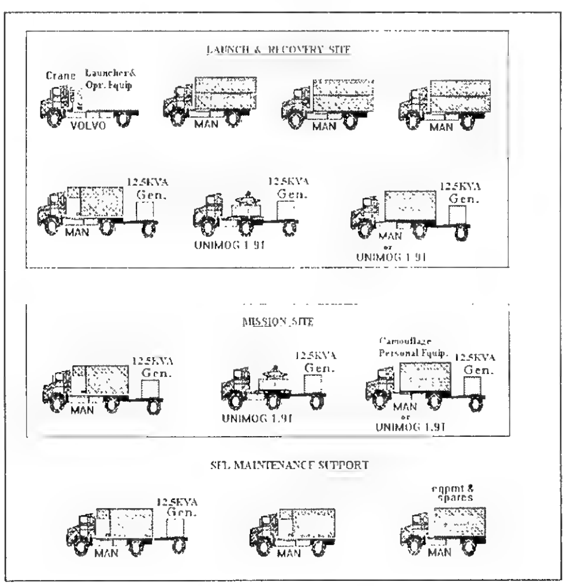

Figure 10. : Load Out Plan

The UAV system will be integrated with vehicles to provide it with autonomous mobility. The vehicles and integration will meet the "all roads" requirement in the foreseen theatres.

The crew for the deployment and the operation of a UAV system consists of 13 persons, 9 for the LRS and 4 for the MCS. Operation of the system, once it has been deployed, requires a crew of at most 6 persons. Refer to the ILSP for minimum training required to operate the system with maximum safety. Deployment and Teardown Times are :

- Deployment time for the MCS (GCS site) is 44 minutes.
- Teardown time for the MCS is 25 minutes.
- Deployment time for the LRS is 90 minutes.
- Teardown time for the LRS is 52 minutes.

The UAV System is capable of being transported by aircraft, type C5, C141 or ANTONOV. Transportation of the system while the elements are mounted on their respective road vehicles is possible up to the maximum height limit of the respective transport aircraft. Transport by Belgian C130 Hercules aircraft without road vehicles.

The components of the UAV system and their associated vehicles may be transportable by rail. All components and vehicles can be loaded into the railway carriages.

Major B-HUNTER UAV Subsystems Elements

3.1. B-HUNTER major subsystems

The B-HUNTER System includes the following major components:

a. Air Vehicle (AV)
b. Payload (MOSP)
c. Portable Ruggedized Control Station (PRCS)
d. Ground Control Station (GCS)
e. Ground Data Terminal (GDT)
f. Ground Support Equipment (GSE)

3.2. Unmanned Air Vehicle (UAV)

The air vehicle (Figure 11) is the remotely-controlled airborne platform of the System. It is a twin engine high wing aircraft. An operational UAV System consists of 6 UAVs. The major groups of equipment which comprise the AV are :

- Airframe
- Propulsion and fuel system
- Electrical Power system

- Digital Central Processing Assembly (DCPA)
- Sensors
- Electromechanical Units
- Airborne Data Terminal (ADT)
- Air Traffic Control (ATC) Transponder (IFF Transponder)
- Flight Termination System

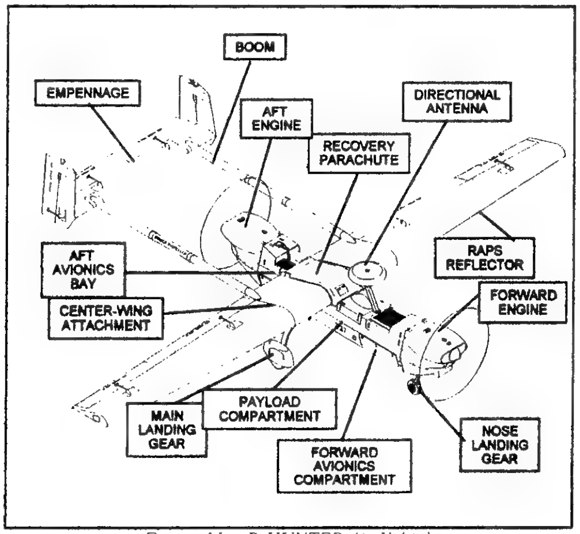

Figure 11. : B-HUNTER Air Vehicle

Airframe

The airframe houses, and supports all airborne equipment within an aerodynamic shape that provides lift and control surfaces. The airframe has a fixed wing and is constructed of lightweight composite materials which allows ease of repair. The airframe consists of the structural elements including fuselage, wing and empennage assemblies required to carry UAV equipment and the payload. The airframe includes a fixed landing gear, an arresting hook and a payload lift.

The UAV is designed to be capable of packaging in the UAV storage/shipping container.

The UAV airframe can be disassembled (fuselage, wing, boom, tail, etc) for storage and transportation in the UAV container.

Propulsion and Fuel System

The AV is powered by two engines. The forward engine drives a two blade tractor propeller and the rear engine drives a two blade pusher propeller. The propellers are two blades laminated wood propellers equipped with Estane leading edge protection. The propellers comply with the requirements of FAR part 35.

The fuel is stored in the integral tank of the center wing and the fuselage and is pumped by the membrane pumps of the carburetors.

Electrical System

The AV electrical power system generates, distributes and controls the required electrical power for the various electrically operated UAV component items including the Payload and the ADT.

For Ground Operation, the UAV is equipped with an electrical power connector enabling the connection of all 28V buses and all DC/DC converter inputs to a 28VDC external (ground) power source.

The UAV is equipped with an emergency battery which supplies critical loads through the 28V battery bus in case of a failure in the generator. The battery supplies the flight critical consumers. The emergency battery is a sealed Ni-Cd battery which is connected in parallel to the generator.

The UAV is equipped with aircraft standard position-lights and a strobe-light.

Digital Central Processing Assembly (DCPA)

The Avionics in the UAV is controlled by the DCPA. The DCPA receives commands from the GCS through the communication system, or uses the stored mission program. The DCPA provides flying qualities that match the specified requirements in all the flight modes. The DCPA is capable of detecting failures of sensor, computer and actuator and has the ability to backup each faulty item. The DCPA status and flight parameters are transmitted to the GCS. The DCPA provides all the required facilities for control and operation of the AV. It manages the important UAV subsystems including the MOSP and the ADT. The DCPA consists of two identical digital computers (AVC1 and AVC2). The two digital computers are connected to each other via a RS-422 digital data link (Cross Channel Data Link). Both computers include software and hardware modules, and I/O cards. During normal operation AVC-1 is the active computer, while AVC-2 is in stand-by mode. All the inputs and most of the outputs are connected to both computers, but only the active computer outputs are actually issued. In the event of a failure in the AVC-1, the AVC-2 becomes the active computer and takes control of all the common outputs, providing a full back-up for the related functions.

Sensors

The AV is equipped with the following sensors:

- Air Data Unit (ADU) includes the airspeed transducer and the altitude transducer
- (pitot system).
- One Vertical Gyro Unit (VGU) providing pitch and roll attitude information for flight control system and for attitude display.
- One Sensor Block containing triple axis rate gyros and accelerometers providing angular velocities and accelerations to back up the flight control system in case of VGU failure.
- The UAV is designed with provisions for replacement of the VGU and sensor block with two Fiber Optic Gyro (FOG) based Directional Measurement Units (DMU). The DMUs provide

redundant pitch and roll attitude as well as three axes rate and acceleration.

- Three axes Flux Valve Unit (FVU).
- Global Position Sensor (GPS) and Antenna.
- Engine Temperature Sensor (ETS) inserted in the engine head.
- Fuel Level Sensor (FLS) inserted in the fuel tank.
- Two accelerometers (X and Y axes) provide the decision to enter to the
- Emergency mode.

Electromechanical Assemblies

The following electromechanical assemblies are installed:

- 6 flight control servo actuators (aileron, rudder, elevator).
- 2 throttle servo actuators (FWD, AFT).
- 2 flap servo actuators.
- Nose wheel steering servo actuator.
- Payload lift actuator.

Airborne Data Terminal (ADT)

Commands, Video images and reports are transferred in real time from and to the GCS/GDT by the airborne section of the communication system, the ADT. The ADT is divided into three major assemblies: the primary ADT receiver; the Backup ADT receiver; and the antenna group - provided as part of the UAV airframe.

Air Traffic Control (ATC) Transponder

The UAV is equipped with an IFF Transponder, capable of operating at 1, 2, 3/A, C, S, 4 and TEST modes. The IDENT and emergency reply codes are in accordance with NATO STANAG 4193 rules. The transponder is controllable by the Pilot Navigator.

Flight Termination System

The UAV is equipped with a Flight Termination System (FTS). In the event of system failure which would preclude a normal recovery, the Flight Termination System (FTS) is activated using a parachute. The FTS is activated by a manual command from the GCS or automatically in the event of loss of link and total DCPA failure. The parachute pack is installed in the parachute compartment in the forward upper section of the UAV. The DCPA is capable of initiating the emergency recovery process according to the operator command received through the ADT, or as part of the Loss-of-Link flight plan, or independently, in the event of system failure. The Flight Terminal Logic (FTL) unit is capable of initiating the emergency recovery process in the event of a system failure that results in total failure of the DCPA itself, or according to a flight termination command received from the Flight Termination Receiver (separately from the normal GDT-ADT data link).. The FTL activates the FTS which performs: UAV payload Lift-up to safety position (Lift-UP command); Cuts UAV engines (FWD and AFT Engine Cut Command) and releases the parachute (Shoot Parachute).

3.3. Multi Mission Optronic Payload (MOSP)

The Multi-Mission Optronic Stabilized Payload (MOSP) is a Day/Night stabilized passive electro-optical system designed to provide the observer with the capability to detect, recognize and acquire tactical targets under day and night conditions. A complete UAV- System includes 6 MOSP.

The payload is installed onboard the UAV and is controlled by an observer in the Ground Control Station. The MOSP:

- Enables the operator to acquire targets during day and night engagements using two fields of view Narrow (NFOW) and Wide (WFOV).
- Provides the capability to track targets either manually by using a joystick or automatically by using the TV tracker with either Camera Lens Assembly (CLA) or Forward Looking Infra Red (FLIR) sensor as image source.
- Provides the capability to select between the CLA image and the FLIR image.
- Provides Line of Sight (LOS) direction (bearing and depression) in reference to the UAV axes.

The MOSP is composed of:

- Stabilized Gimbals Assembly (SGA) containing Stabilized Platform Assembly (SPA) and Payload Control and Logic (PCL)
- Forward Looking Infrared (FLIR) containing 2nd generation 8-12μ Thermal Sensor Unit (TSU) and FLIR Electronic Box (FEB).
- Camera Lens Assembly (CLA) containing TV camera and 20mm-280mm continuous zoom lens.
- Tracker contained in PCL.

3.4. Ground Control Station (GCS)

The GCS is a shelter type control station mounted on a 4-ton MAN vehicle. The shelter configuration is capable of supporting electronic equipment installations and protection of the operators in the specified environment. Two identical GCS are provided with each UAV System, where one unit is employed at the launch and recovery site and is used for the pre-flight, take-off and landing, while the other is used for the mission planning, mission control and observation.

Shelter

The shelter is S 280 type shelter with consoles for 3 operators. The shelter is transportable by a MAN 4T.

The shelter is air conditioned. The shelter provides all necessary electrical and mechanical interfaces for the

BAMS tactical communication equipment.

Operators' Consoles – OPBY-R/L, CMBY

The GCS uses a generic console as a building block. The generic console has all the hardware and all the software needed to control the UAV, its payload and also the datalink. The GCS has two generic consoles each of which may be configured to perform all the mission and flight critical functions. If mission critical hardware fails in one generic console, it is possible to reconfigure the system so that the second generic console takes over the functions of the failed hardware. A third console contains hardware that is not critical for the safety of the UAV or for its mission. The GCS configuration includes three operators' consoles as depicted Figure 12.

Generic console	Commander console	Generic console
OPBY- L	CMBY	OPBY- R
=	=	=
Real Time Observer	Mission Commander	Pilot Navigator + Mission Planner
-or-	+	-or-
Pilot Navigator + Mission Planner	Mission Planner	Real Time Observer
	+	
	Off Line Analyst	

Figure 12. : S 280 Shelter, Mission Console Assignment

An operator will be stationed at each console, i.e. 3 operators.

The functions for the left generic console and the right generic console are software assigned.

In a typical configuration, the generic console on the right will assume the functions of Mission Planner + Pilot Navigator and the generic console on the left will assume the functions of the Real Time Observer. The functions of the Mission Commander + Mission Planner + Off Line Analyst are assigned to the central console. The generic consoles are symmetric, so their functions can be exchanged between left and right. The functions of the Mission Commander and of the Off-Line Analyst may also be available at any of the other consoles.

Instructor Bay (INBY)

The INBY bay contains the necessary instrumentation for connection to and switching of the up-link and down-link data between the operators bay via the TLM-SW. The bay is also used to host two 50W BAMS radios see GCS SSDD.

Supplies Bay (SBY)

The SBY bay is the electrical power center for the GCS. It hosts the 230 VAC to 28 VDC power converters, a battery pack, five UPS for all bays and the electrical control panel.

Operator Proficiency Simulator (OPT)

The Operator Procedure Trainer (OPT) consists of a commercial Personal Computer and interface components. When connected to the GCS it enables the operators to perform their respective functions as if an AV was in flight. The OPT also simulates the function of the GDT. The three consoles of the GCS send commands to the OPT (as if it were an AV) and receives the appropriate responses (data, status and video). Thus, the operator is able to operate the system, in all the modes of operation that are pertinent to an AV in flight. Delivery of an OPT can significantly reduce the risks associated to human errors by appropriate training of all the mission operators involved in a UAV battalion.

TACOM

The GCS includes a full duplex intercom system, based on SOTAS system, for voice communication among the operators.

3.5. Ground Data Terminal (GDT)

A complete UAV- System consists of 2 GDTs (Figure 13), each connected to an GCS. The GDT is mounted on a UNIMOG and integrated with a vehicle mounted DC Generator (Figure 14).

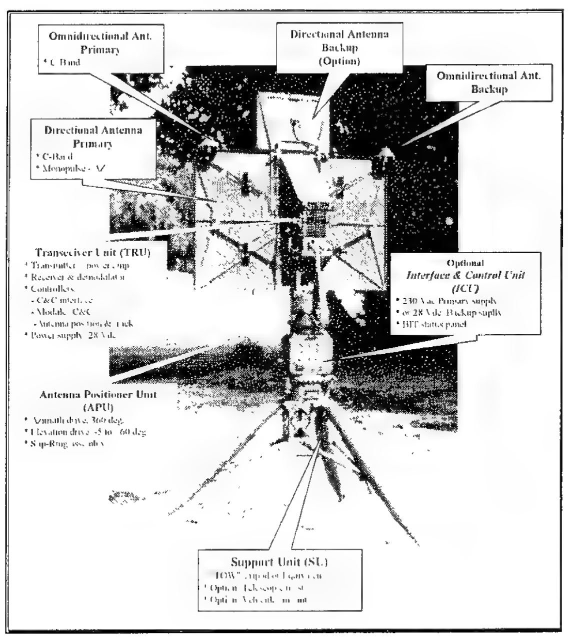

Figure 14. : Ground Data Terminal

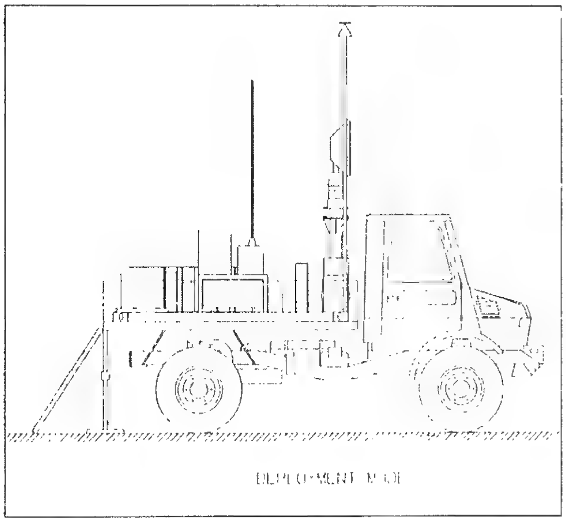

Figure 15 : GDT on UNIMOG Truck (Deployment mode)

The communication between the Ground Control Station (GCS) and the UAV flows via the Ground Datalink Terminal (GDT) and the Airborne Datalink Terminal (ADT). It is designed to provide full duplex communication link between the UAV and the GCS. The GDT transmits to the ADT two uplink channels and receives from it a single downlink channel. The uplink channel includes the real time command and the control message. The downlink channel includes real time video and telemetry.

The functions of the GDT are as follows:

- Receiving the uplink message and the ground Datalink control from the GCS via RS422 protocol.
- Transmission of real time primary command uplink (UPL-1) to the UAV via the radio link.
- Transmission of real time secondary command UPL-2 to the UAV via the radio link.
- Receiving real time down link (DNL) information (video and telemetry) from the UAV via the radio link.
- Transmitting the downlink message (video and TM) and Datalink status to the GCS via RS422 (TM) and CCIR format (VIDEO).
- Tracking the UAV transmitted RF signals.
- Measure the azimuth and range from the GDT to the UAV.
- Execute the Built In Test function.

The GDT major elements are:

a. Antenna System
   - Directional Antenna (C band) (for UPL & DNL)
   - Omni directional Antenna (C band) (for UPL & DNL)
   - Omni directional (UHF) (for backup UPL only)

b. Transceiver Unit (C band)
c. Directional Antenna Positioner
d. Backup Transmitter (UHF)
e. Digital Video Expansion Unit
f. Equipment Box
g. Power Supply Unit
h. Generator

3.6. Portable Ruggedized Control Station (PRCS)

The PRCS is a computer station for on-line mission management (planning, ordering, reporting, overlays sending and receiving) remotely from the GCS. It provides a computer terminal for communication with the GCS via the Battery technical net and the Intelligence net radio networks, using the QUICK DATA BAMS 50W radio.

The PRCS is used by the Battery Commander to transmit Operational Orders (OO) to 3 operational GCS of his Battery. The PRCS is used by the ASIC to receive and exploit information from 3 operational GCSs in the Battery. The PRCS is based on a workstation, using UNIX as the operating system, and on a subset of the GCS software for mission planning. The PRCS software uses the same resources used by the GCS software for mission planning. The PRCS can be carried by one person.

3.7. Ground Support Equipment (GSE)

Launcher

The B-HUNTER uses a specifically designed HUNTER launcher for RATO take-off.

RAPS (Figure 16)

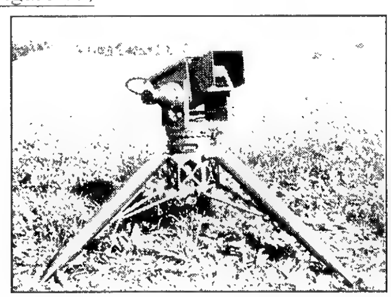

Figure 16 : Range Automatic Positioning Sensor

The ground portion of the RAPS consists of the following elements:

- Tripod - serves as a basis for the sensor platform
- Sensor Platform with Transportation Case - Contains Actuator Motors, Position Sensors, Gears and Sensing Head
- The CORA Sensing Head - Consists of Laser Diode Emitter, Distance Sensor, Angle Sensor, and TV

camera
- Electronic Unit with Transportation Case - Encompasses Compact electronic cabinet with embedded computer and interface electronics for actuators and sensors
- Battery Pack - provides electrical energy to RAPS

The airborne portion of the RAPS consists of a retroreflector, mounted in the UAV wing leading edge and used to reflect the laser beam to the RAPS ground portion.

Other Ground Support Equipment
The B-HUNTER UAV Single Field Level of maintenance concept consists of the following (see also Figure 10) per B-HUNTER UAV System :

a) GFE Supplied Volvo 10T with 10T Crane for
    - Launcher
    - Support Equipment
b) 3 GFE MAN 5T Trucks, each capable of transporting 2 UAV Containers
c) LRS : One GFE Truck for GSTE and operational equipment incl. Flight Line Tester
d) MCS : One GFE Truck for personnel and camouflage equipment
e) Mobile and Maintenance Facility
    - One Mobile Workshop :
        - S280 Shelter on GFE MAN 5TTruck
        - Maintenance Tent
        - PC and GSTE
    - One Mobile Storage Facility for :
        - Support Equipment
        - Spare parts
    - One GFE Cargo truck for GSTE and Spare parts

Airworthiness Certification Process

4.1. Introduction

The worldwide UAV community faces today to the civil airspace management and regulations organization demands to be able to make fly their Air Vehicles in the civil air space, over populated areas. Flying UAVs is in most of the case still restricted over dedicated areas which belong to military organisations. Deployment of UAV systems in the civil airspace over populated areas is one of the major challenges UAV manufacturers will have to comply in the very future.

By reaching this goal, there is no doubt that this will allow not only military users to extend the range of their systems, but also will significantly increase the potentialities of UAV systems to perform safely civil applications which today cannot be achieved mainly because restrictions are still imposed to deploy safely UAVs above populated areas.

Definition of UAV Systems certification rules by international regulation authorities and compliance of UAV Systems to these rules is a major objective of the next century, should all the UAV users and manufacturers want to extend the application range and the market of future UAV Systems.

4.2. The B-HUNTER UAV System Certification Process.

The B-HUNTER UAV System airworthiness can today hopefully count on the fact that the HUNTER UAV System accumulates an experience of more than ten thousand (10.000) flight hours which are the combined result of a two engines concept which has undergone extensive endurance tests according to the FAR 33 standard, of built in redundancies included in all safety critical items of the system, of an emergency parachute tested and approved. The Air Traffic Control (ATC) mode ¾ IFF and the anti-collision strobe lights allow already the HUNTER System to be integrated in the US civil air space.

During all stages of its customisation to the Belgian Ground Forces needs, the B-HUNTER UAV System will follow an extensive Airworthiness Certification process in order to comply with an overall safety objective consisting of the following : "The B-HUNTER UAV System must allow during all its life safely execution of UAV missions above populated areas taking into account Belgian environmental conditions".

The goals of the airworthiness activities to be held in the course of the B-HUNTER Program are the granting of two certificates required by the Belgian law which defines the legal airworthiness requirements to which UAV systems have to comply :

a) the Airworthiness Type Certificate
b) the Individual Airworthiness Certificates which shall include
    - the initial Individual Airworthiness Certificate
    - the Maintaining of the Aptitude to fly

4.3. Airworthiness Type Certification

The following steps are to take place towards the granting of Type Airworthiness Certificates according to the following logic structure:

1. Definition of certification basis composition containing the following elements :
    1) System Safety Program Plan (SSPP)
    2) Tailored JAR-VLA compliance elements

3) Specific Requirements
4) Relation with logistics support.

2. Definition of methods and levels of verification as well as verification procedures for all elements of the certification basis
3. Execution of the verification plan related to the basis of certification (including analyses and tests reports)
4. Compilation of the final Certification File including all elements as defined in paragraph 11.2.5.
5. Presentation of the Certification File and the airworthiness type certificate for approval by BMOD certification authority (GST).

These activities will be executed in close coordination with other Program engineering activities in order to :

- Reach the Overall System Safety Objective for the B-HUNTER UAV System
- Establish accordingly the Final Certification File that will serve as a justification for the granting of the Airworthiness Type Certificate.

A. Certification basis

System Safety Program activities

Those activities are related to the risk analysis are detailed in a System Safety Program Plan based on the Contract requirements and on required MIL STD 882C tasks. Specific Safety Analyses outputs are :

- System Hazard Analysis and Sub System Hazard Analysis (SHA & SSHA)
- Operational Support Hazard Analysis (OSHA)
- Safety Assessment Report (SAR)

The hazard probability is a qualitative expression of the probable occurrence of the identified hazards during the planned life expectancy of the system in accordance with MIL-STD-882C, paragraph 4.5.2.

The application for B-HUNTER program is presented in Table 1, below.

DESCRIPTION	LEVEL	SPECIFIC INDIVIDUAL ITEM	FLEET OR INVENTORY
FREQUENT	A	Likely to occur frequently.	Continuously experienced
PROBABLE	B	Will occur several times in life of an item.	Will occur frequently.
OCCASIONAL	C	Likely to occur sometime in life of the item	Will occur several times
REMOTE	D	Unlikely, but possible to occur in life of the item	Unlikely, but can reasonably be expected to occur
IMPROBABLE	E	So unlikely, it can be assumed occurrence may not be experienced.	Unlikely to occur, but possible

Table 1 : Hazard Probability

The hazard severity categories are tailored as per MIL-STD-882C requirements. The application for B-HUNTER program is presented in Table 2 below.

DESCRIPTION	*Category*	*Software Safety Criticality (sec 3.4)*	MISHAP DEFINITION
POTENTIALLY CATASTROPHIC	I	*Critical*	Uncontrolled UAV landing or crash
CRITICAL	*II*		Failure conditions which would reduce the capability of the UAV to cope with adverse operating conditions to the extent that there would be a large reduction in safety margins or functional capabilities, or cause severe injuries
MARGINAL	*III*	*Non Critical*	Failure conditions which would reduce the capability of the UAV to cope with adverse operating conditions to the extent that there would be a significant reduction in safety margins or functional capabilities, or cause system damage and possible minor injuries
NEGLIGIBLE	*IV*		Failure conditions which would not significantly reduce UAV safety, and which may lead to a slight reduction in safety margins or functional capabilities, or cause less than minor injuries

Table 2 : Hazard Severity

Software components are classified as:

(a) Safety Critical Software, i.e. software whose anomalous behavior as shown by functional hazard assessment would cause or contribute to a failure condition of category I or II as defined in Table 2.
(b) Non Safety Critical Software i.e. software whose anomalous behavior as shown by functional hazard assessment would cause or contribute to a failure condition of category III or IV as defined in Table 2.

Acceptable risk levels can be deducted from the matrix, presented in Table 3, as per MIL-STD-882, which depicts the risk levels (index), as a function of hazard probability and severity class and the requested actions for each risk category (Table 4).

HAZARD PROBABILITY	HAZARD LEVEL			
	I *Potentially* Catastrophic	II Critical	III Marginal	IV Negligib
A-Frequent	1A (1)	2A (3)	3A (7)	4A (13)
B-Probable	1B (2)	2B (5)	3B (9)	4B (16)
C-Occasional	1C (4)	2C (6)	3C (11)	4C (18)
D-Remote	1D (8)	2D (10)	3D (14)	4D (19)
E-Improbable	1E (12)	2E (15)	3E (17)	4E (20)

Table 3 : Acceptable Risks Level

HAZARD RISK INDEX	ACTION REQUESTED
1-3	High Risk – Unacceptable
4-6	Medium Risk – Undesirable (Managing Activity decision required)
7-17	Moderate Risk – Acceptable with Managing Activity review
18-20	Low Risk – Acceptable without review

Table 4 : Risks Level Management

Risk level Management is the basis of all the safety assessment activities to be performed in the frame of the B-HUNTER UAV Program which are depicted in Figure 17 here under which provides interrelationship between engineering activities and Integrated Logistics Support Activities with the safety analysis tasks to be performed in the frame of the B-HUNTER UAV Program :

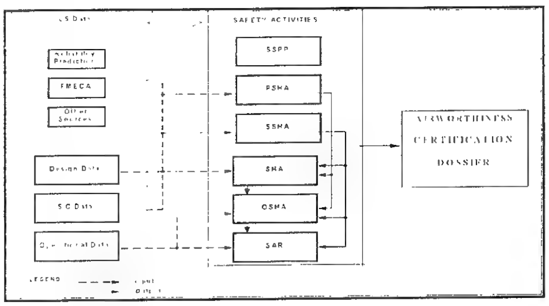

Figure 17. . Safety Activities Interrelationship

Presentation of a Tailored JAR-VLA

There currently don't exist any Joint Air Regulations related to UAV Systems. During the course of the B-HUNTER UAV Program, a tailoring of the existing Joint Air Regulations for Very Light Aircrafts (JAR VLA) will be made more specifically with regard to the B-HUNTER UAV System. Identification of the B-HUNTER UAV System compliance to the JAR VLA requirements is performed.

Specific Requirements

Attention will be paid in the frame of the airworthiness type certification to the following items :

(1) Fail safe design
(2) Built in Test
(3) Software
(4) Flight Management System
(5) Electrical System
(6) Communications/Datalink
(7) Navigation System
(8) Propulsion System
(9) Ground Control Station (GCS)
(10) Flight Recovery and Termination System
(11) UAV air vehicle

Impact on logistic support

The Contractor will also execute the activities foreseen in view of the functional, technical and logistics requirements of the Contract which are related to Airworthiness Type Certification.

B. Airworthiness Verification Activities

Verification methods and levels as specifically related to Airworthiness requirements will be reviewed and will be included in the overall Program Verification Plan.

Specifically required airworthiness procedures will be identified with regards to related to airworthiness requirements and will be integrated within the verification procedures and activities taking place in the frame of compliance demonstration with the functional, technical and logistics requirements of the Contract.

Analyses, demonstration, tests or inspection on all airworthiness related items will be performed according to an Airworthiness Verification Plan.

Credit will be taken from the existing data and emphasis will be put on the specific adaptations from the HUNTER Baseline configurations to the B-HUNTER UAV System. Credit from existing data supposes that the configuration items to which similarity is referred are equivalent to the one of the B-HUNTER Contract;

C. Final Certification File

A final Certification File will be subsequently established. Upon this basis, the Airworthiness Type Certificate will be granted by which it is attested that the B-HUNTER UAV System in its final configuration satisfies the above mentioned Overall Safety Objective.

The final Certification File shall be fully adapted to the B-HUNTER UAV System and shall include the following information :

(1) An identification and reference to the B-HUNTER UAV System configuration.
(2) The certification basis containing compliance statement, and summary of related compliance demonstration related to airworthiness requirements namely :
    - System Safety Program requirements
    - Tailored JAR/VLA
    - Demonstration of B-HUNTER UAV System Compliance to airworthiness requirements
    - Operational, Technical and Logistical requirements shall also be taken into account.
(3) Verification levels and methods used to prove compliance to the contract requirements related to airworthiness
(4) Reference to the corresponding substantiation data (test results and analyses)
(5) Airworthiness Type Certificate attesting that the B-HUNTER UAV System, in its final configuration satisfies with the Overall System Safety Objective with :
    - Reference to the B-HUNTER UAV System configuration, with mention of the limitations of its performances and characteristics;
    - Mention of the conditions or restrictions relative to the deployment of the B-HUNTER UAV System;
    - Reference to the procedures which permit to cope with these limitations or restrictions;

- Reference to the requirements (certification basis) which constitute a sufficient basis for system airworthiness.

4.4. Initial Individual Airworthiness Certificates

Individual Airworthiness Certification will be based upon Quality Control / Conformity Inspection activities to ensure that each individual system has been built in accordance with the Technical Definition Dossier and upon Acceptance Tests.

In order to demonstrate that each individual air vehicle and the associated UAV system satisfy the requirements concerning official initial individual certification, necessary test and analyses, including flight tests are to be made before delivery.

After these initial individual test, an individual certification file shall be drawn up and shall be delivered along with the relevant system and UAV air vehicle.

4.5. Preservation of Flight Capability

Preservation of flight capability means that periodically (every fifty flight hours) the individual airworthiness certificate has to be renewed by the Ground Forces.

The following requirements have to be fulfilled for preservation of flight capability :

(1) User regulations, the content of which has been determined, have to be formulated for the UAV system.

(2) Maintenance and support regulations must be defined.

(3) The requirements concerning the qualification of the personnel responsible for the operation and the maintenance of the UAV system are to be met. This applies to the establishment of the responsibilities and the correct filling in of the necessary certificates.

(4) Control Systems must be defined to make possible the control of the following:
    - Compliance with the user's regulations
    - Compliance with the maintenance and supply regulations
    - The application of an updating system for maintenance and supply documents
    - The description of every alteration and its approval by the personnel of the Ground Forces responsible for the management of the definition file
    - The inclusion of these alterations in the definition file and in the maintenance and supply documents
    - Compliance with the requirements concerning the qualification of the personnel

Conclusions

This paper has presented the B-HUNTER UAV System that will be delivered to the Belgian Army Ground Forces from year 2001, and the main adaptations or customisations that will be done with regards to the US HUNTER Short Range Tactical UAV or to the F-HUNTER UAV System. An overview of the B-HUNTER main subsystem has been described together with its performances.

Airworthiness Certification is a Belgian legal condition before to be authorised to fly in Belgium over populated areas and is consequently an essential part of the Program. The airworthiness certification process which has to conclude to a final safety assessment has been detailed. The activities performed in the frame of the B-HUNTER UAV program will contribute to the execution in safety conditions of the Belgian Ground Forces missions in the frame of their participation to future NATO peace keeping missions, and, why not, of future civil missions in Belgium in a UAV controlled Air Space Management.

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Airspace	Remotely operated vehicles
Air traffic control	Robots
Command and control	Detectors
Optimization	Reynolds number
Systems analysis	Aerodynamic characteristics
Computer architecture	Synthetic aperture radar
Design	Drone aircraft
Airworthiness	Command control communications
Payloads	Airbreathing propulsion
Control equipment	

14. Abstract

Lecture Notes for the RTO Applied Vehicle Panel (AVT) Special Course on "Development and Operation of UAVs for Military and Civil Applications" have been assembled in this report. The following topics were covered: Overview of current UAV systems and potential for the future, Design and airworthiness requirements, Propulsion systems, Airbreathing propulsion for UVAVs, Microflyers, Experimental research at low Reynolds numbers, Payloads and sensors, Datalinks, Airspace policy, Air traffic management and Tools for software and system architecture validation.

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